CORRELATION OF STRUCTURAL LINEAMENTS AND FRACTURE TRACES TO WATER-WELL YIELDS IN THE EDWARDS AQUIFER, CENTRAL TEXAS

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For Carmen, whose patience, love, and
encouragement made this thesis possible

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by

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ABSTRACT

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Lineaments are "straight lines visible from afar on the surface of the earth". In the Austin, Texas area, lineaments reflect the structural grain of the Balcones-Ouachita fault zone and may indicate subsurface geologic phenomena such as faults, fractures, and joints. These structural features often represent discrete zones of high permeability, and thus, areas of enhanced flow of groundwater capable of transmitting greater quantities of water than surrounding, non-fractured, rock.

For this study more than 900 lineaments and fracture traces, identified in aerial photographs during a previous study, were detected in the Barton Springs section of the Edwards Aquifer. The endpoints of each linear feature were digitized and tagged with a unique identification label. Rose plots, Cartesian histograms, and a series of statistical operations were utilized to illustrate regional trends in the orientation of lineaments. As an indicator of well productivity, specific capacities of 27 wells in the area were obtained. Sixty-one water samples were collected and analyzed to test for possible chemical evidence of lineament-well interactions.

The orientations of lineaments and fracture traces in the study area clearly display a bimodal distribution with a primary trend of N 40 E and a secondary peak of N 50 W. A general correlation exists between increased well productivity and decreased distances to the nearest lineament, particularly within 200 feet of lineaments. Also, 10 of the 13 largest specific-capacity values are from wells located southeast of southwest-northeast trending lineaments. Nonparametric statistical methods show that direction from lineaments is a significant factor in predicting water-well yields.

Lineaments provide a tool for predicting possible sites of environmental sensitivity with respect to groundwater resources. Examples include the siting of groundwater monitoring wells for point sources of pollution, predicting the likely underground flow paths of a pollution plume or locating dam sites for recharge enhancement. Awareness of the location, orientation, and density of structural lineaments will allow the water-resource manager to identify discrete groundwater flow paths, and, thus, predict contaminant plume migration.

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I. INTRODUCTION

This study investigates the association between structural lineaments and water well yields in the Barton-Springs segment of the Edwards aquifer. Lineaments, in simplest terms, are "straight lines visible from afar on the surface of the earth" (Woodruff & Caran, 1984). In the Austin, Texas area, lineaments reflect the structural grain of the Balcones-Ouachita fault zone and may indicate subsurface geologic phenomena such as faults, fractures, and joints. These structural features often represent discrete zones of high permeability, and thus, areas of primary groundwater movement capable of transmitting greater quantities of water than surrounding, non-fractured rock.

Lineament analysis can be a useful tool for the hydrogeologist. The technique is especially valuable for predicting possible sites of environmental sensitivity with respect to groundwater resources. Examples include the siting of groundwater monitoring wells for point sources of pollution, predicting the likely underground flow paths of a pollution plume or locating dam sites for enhanced recharge. Lineament analysis may also be used to increase the probability of drilling large yield water wells. Consequently, the location, orientation, and density of structural lineaments may be valuable in forecasting problems with quantity as well as quality of groundwater.

In many areas in the Edwards aquifer, groundwater is available in sufficient quantities to make the process of locating wells to extract small yields of water a relatively simple task. However, other areas appear to have a limited amount of groundwater available and considerable difficulty can be experienced in obtaining an adequate water supply without drilling several wells. One serious problem with the use of groundwater as a source of water supply in the Edwards is that well yields vary tremendously. Wells with yields ranging from 2 and 500 gallons per minute (0.13 and 31.5 liters/second) can commonly be found within a short distance of one another. When larger yielding wells are required to meet the water needs of a subdivision, an industry, or a small town, the problem of obtaining sufficient well yields becomes even more difficult. The typical approach is to drill either a single well with a sufficiently high yield or drill several wells so that the combined yield will meet the estimated water needs. This approach is expensive and frequently not successful. If a procedure was available that would increase the likelihood of obtaining a higher yield in each well drilled, it would reduce the cost of developing groundwater as a source of water supply and decrease the probability of failure to acquire the quantity of water required.

The expense of drilling several dry holes or wells with an inadequate yield to satisfy the owner's water needs can become quite large. The typical cost of a drilled well ranges from one to five thousand dollars or more depending on the depth of the well. Therefore, the ability to obtain the required well yield with as few drilled wells as possible is an important factor in determining the economics of groundwater as a water supply. One goal of this research project is to develop a technique that can be used to locate well sites that have a higher probability of producing large yields so that the cost of developing groundwater supplies can be minimized. Reliable methods of detecting the major groundwater flow zones in the Edwards aquifer are needed for the most economical development of its groundwater resources.

A) Previous Lineament Studies in Central Texas

Previous studies of lineaments in Texas investigated (1) the effects of Balcones faulting on linear features (Wermund *et al.*, 1974, Collins & Laubach, 1990), (2) parallelism between the trends of lineaments and structural features (Dix & Jackson, 1981, Myrick *et al.*, 1988), (3) correlation between lineaments and faults (Caran *et al.*, 1982; Kreitler, 1976), and (4) the relationship between lineaments and geothermal potential (Woodruff & Caran, 1984).

In the Barton-Springs segment of the Edwards aquifer, the relationship between lineaments and transmissivity was first investigated by De La Garza and Slade (1986a). Controlled aerial mosaics were used to map two sets of lineaments. Transmissivities of 47 wells were then estimated from specific-capacity data obtained from drilling records. After determining the distances from each of the wells to the nearest lineament, a correlation was found between increased well productivity and decreased distances to "short" lineaments (between 1000 feet and 4.5 miles (30 meters and 7.2 kilometers) in length).

More recently, Woodruff *et al.* (1989) examined the effects on lineaments in the Edwards aquifer by (1) orientations of faults and joints, (2) drainage patterns, (3) topography, and (4) hydrology.

B) Research Objectives

The objective of this study is to expand a previous lineament study of the Edwards aquifer (De La Garza & Slade, 1986) by acquiring reliable data for specific-capacity and water-chemistry for as many wells as possible and accurately mapping and transferring the resulting data to a base map. In addition, this study will include statistical and chemical analyses to further investigate any conclusive evidence of lineament-well yield correlation in the Edwards aquifer. Specific objectives are to:

- Examine statistical relations between values for well yields and lineaments of different types, lengths, and orientations
- Investigate possible groundwater flow paths using chemical analysis
- Develop a predictive model for well yields in the karstic Edwards aquifer

II. Lineaments and Fracture Traces

A) Background Information

Terminology

There is a substantial amount of misleading terminology on linear features in the literature which has proliferated since the advent of spacecraft and high-altitude imagery. Part of the confusion with lineaments is a result of semantics. For example, a lineament is not necessarily a fault. Nor is any single lineament a single fracture or joint in the bedrock. Faults and joints may be expressed as lineaments, "but the term 'lineament' implies that the precise geologic nature of each individual feature is ambiguous" (Woodruff, 1989). Structural lineaments are simply surface manifestations of subsurface geologic features such as faults, fractures and joints.

O'Leary *et al.* (1976) reviewed the origin and usage of the terms linear, lineation, and lineament. They have attempted to standardize the terminology by strictly defining each expression. For this study, their definition of lineament will be used:

> A *lineament* is defined as a mappable simple or composite linear feature of a surface, whose parts are aligned in a

> straight or slightly curving relationship, and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon.

Furthermore, the structural lineaments reviewed in this study will be divided as recommended by Parizek (1976): linear features less than 1500 meters (4922 feet) will be classified as fracture traces; longer than 1500 meters will be classified as lineaments.

Lattman (1958) noted that the term fracture trace is used as opposed to the term fracture because the surface expression of the linear feature is an indirect indication of some subsurface discontinuity. The fracture is not observed except in the case of features that are mapped on aerial photographs of an area where bare bedrock is exposed at the surface. Because the true nature of the subsurface discontinuity is usually unknown, the linear feature on the ground surface is more appropriately identified as a fracture trace. In an analogous manner, the term lineament simply identifies a long linear feature on the surface of the earth that is associated with a long subsurface discontinuity that may be continuous or discontinuous and for which the origin and characteristics are unknown.

Structural Controls

Although the nature of the subsurface discontinuity associated with a fracture trace or lineament cannot be observed under normal circumstances, there have been a number of situations where the characteristics of the subsurface feature could be examined. These situations have typically occurred where a fracture trace or lineament intersected a vertical cliff, deep highway cut, rock quarry, or some other type of excavation that would expose a cross-section of the discontinuity for a considerable depth. Several investigators have found examples of exposed subsurface discontinuities associated with fracture traces and lineaments and have described the nature of the features. Lattman and Matzke (1961) found a zone of joint concentration underlying a fracture trace for which a cross-section was exposed by a vertical cliff in sandstone in Wyoming. The fracture trace was expressed as an alignment of drainage features along a straight, shallow, topographic trough on the aerial photographs.

The apparent linearity of lineaments and fracture traces, regardless of topography, was interpreted by Trainer and Ellison (1967) as an indication that the associated fracture zones are vertical or nearly vertical. In addition to the vertical fractures, the fracture zones usually contain a series of horizontal joints that connect adjacent vertical fractures (Figure 1). This is an important characteristic when the objective of a well-drilling program is to intersect one or more fractures with a vertical well.

The characteristics of the subsurface fracture zones also appear to vary by rock type. Situations have been observed in which a subsurface-fracture zone consisted of closely spaced fractures in one rock type and more widely spaced fractures in another rock type at a different elevation within the same fracture zone (Stafford *et al.*, 1983). The

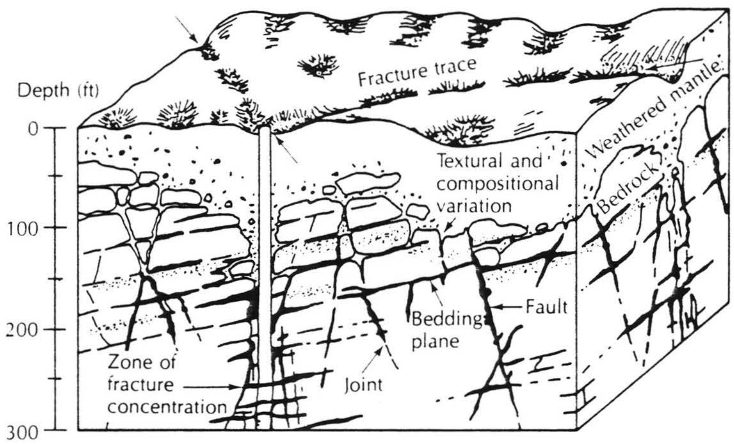


Figure 1: Conceptual diagram of groundwater along fracture zones in carbonate rock (from Lattman & Parizek, 1964).

fracture zone is generally connected to the layer of residual soil at the soil-rock interface so that the soil layer can serve as a groundwater recharge zone for the fractures in the rock. In fact, there is usually a deeper layer of residual soil along lineaments and fracture traces than in adjacent areas. Apparently the fractured rock along these natural linear features weathers more rapidly to produce a layer of saprolite. The more rapid weathering of the rocks within the fracture zones is one reason that many lineaments and fracture traces occur as linear topographic depressions. In turn, these depressions provide enhanced opportunity for groundwater recharge along the natural linear features.

Moore and Stewart (1983) examined a Floridian limestone aquifer and noticed increased dissolution of the underlying limestone directly below a fracture trace. Using surface geophysical techniques, they found that the linear, surface feature had been propagated upward through 20 meters (66 feet) of overburden. Trainer (1967) concluded that extensive weathering of vertical fractures near the surface was probably accompanied by subsurface weathering and possible widening of other fractures that are not expressed as fracture traces. Thus, the existence of a fracture trace at the surface typically indicates that a number of open fractures are present in the underlying bedrock.

Historical Research

The geologic study of lineaments has its ultimate origins in Britain during the period from 1800 to 1835 where a small number of influential geologists established that, in general, there is a system to the pattern and distribution of faults and joints and that these systems can maintain remarkably constant azimuths over significantly large areas (Hodgson, 1974). The systematic arrangement of fractures and faults, which was well documented by 1835, allowed William Hopkins to develop an advanced mechanical theory to account for the phenomena. In 1841, he published a map of the Wealdon Dome that shows directly the orthogonal relations of the major linear features of the region as predicted by his theory. The map appears to be a first attempt to show lineaments directly and in relation to other structures.

William H. Hobbs (1904) has been generally credited with the introduction of modern techniques of study of natural linear features.

He recognized the existence and significance of linear geomorphic features that were the surface expression of zones of weakness or structural displacement in the crust of the earth. He defined lineaments as "significant lines in the earth's face" and added that:

> These significant lines of landscape which reveal the hidden architecture of the rock basement are described as lineaments. They are character lines of the earth's physiognomy.

John L. Rich (1928) was apparently the first geologist to report on the observation of linear features from the air. He recognized linear vegetational, tonal, and topographical alignments while flying over the limestone areas of Oklahoma. He suggested the use of aerial photographs to further study these linear features which he related to bedrock jointing. Little work was done using Rich's idea until the major oil companies became interested in the use of fracture trace studies for their exploration programs in the 1950's. Lattman and Olive (1955), Blanchet (1957), Mollard (1957), and Lattman (1958) all described interpretation of linear features in various geologic terranes.

In 1964, Lattman and Parizek established the important relationship between the occurrence of groundwater with lineaments and fracture traces for carbonate aquifers. Based on analyses of 13 wells in the State College, Pennsylvania area, they determined that lineaments and fracture traces are underlain by zones of localized weathering, increased permeability, and porosity. In fact, they found specific capacities of wells situated along fracture traces to be 10 to 100 times greater than those of wells sited off the lineament trends. Three bore-hole caliper logs obtained from wells drilled on fracture traces confirmed that numerous cavernous openings were penetrated by these wells, which reached 350 feet (107 meters) in depth. As expected, caliper logs from wells drilled in interfracture areas showed few cavernous openings. However, according to Taylor (1980), their investigation had two basic deficiencies: (1) There was an insufficient number of wells intentionally located on and off fracture traces; (2) Little attempt was made to separate the influence of fracture traces from other hydrogeologic variables that affect well yields.

From an analysis of data for 80 wells in the Nittany and Penns Valleys of central Pennsylvania, Siddiqui and Parizek (1971) found that fracture-trace wells were far more productive than nonfracture-trace wells and that the probability of obtaining a certain productivity is greater in fracture-trace wells than in nonfracture-trace wells. They point out that large productivity reflect large porosity and permeability around a well bore and argue that fracture traces must reflect underlying zones of increased porosity and permeability in the bedrock. A basic problem with this study is that many of these hydrogeologic factors are not easily separated which results in the authors having to make certain assumptions that are not acceptable to all investigators (Taylor, 1980).

The effect of lineaments on water-well productivity was also investigated by LaRiccia and Rauch (1977). They examined 65 domestic wells in the Grove and Frederick limestones of Frederick Valley, Maryland. Specific-capacity values were found to be significantly larger for pumped wells within 100 feet (30 meters) of a lineament compared to more distant wells. Since then, many other studies have confirmed that remotely-sensed linear features are reliable indicators of areas of increased groundwater flow (Wermund *et al.*, 1978; Caran *et al.*, 1982; Hunter & Gutierrez, 1985; Wright, 1985).

B) Lineament Analysis

Remote Sensing

The interpretation of lineaments is conducted from a remote vantage point. This remote view allows linear features to be perceived from a variety of clues. These features include dark or light lines in the soil, alignments of vegetation, topographic sags, aligned gaps in ridges, straight stream reaches, and other similar characteristics. Often these linear features are expressed on photographs and on the ground by a combination of features. For example, a straight stream segment may extend into soil tonal alignments in an adjacent field, which then passes into a line of slightly larger trees in a nearby wooded area, ending in an elongated sinkhole.

While there are many types of aerial imagery available, there are only a few types that work well for fracture-trace mapping as applied to water-well location. Lattman's (1958) paper describes in detail the technique of mapping fracture traces. Briefly, fracture traces and lineaments are best mapped by stereoscopic examination of individual aerial photographs. Direction of flight-line overlap of at least 50 percent is necessary in order to obtain complete coverage of each photograph, with 20 or 30 percent of side lap if more than one flight line is to be analyzed. Because some of the features are only a quarter to a third of a mile in length, they are best mapped on aerial photographs at a scale of 1 to 20,000 (1" = 1667'). Photographs are available for most of the United States at this scale. The examination is accomplished using a 2.5 power lens stereoscope and moving the instrument systematically over the photographs, mapping all linear features visible at each position. In addition, stereoscopic study allows the recognition of man-made linear features, bedrock schistosity, outcropping edges of dipping beds, and other features that should not be mapped as fracture traces or lineaments.

Physiographic Expressions

Probably the most obvious expression of fracturing visible on aerial photographs is short, straight, segments of streams and rivers. A prominent joint set or fault can markedly affect the direction of stream flow, and unusually straight segments in a drainage pattern invariably indicate some type of structural control.

As previously noted, fracture traces are also expressed by the alignment of vegetation presumably due to a slightly higher concentration of moisture. A much more subtle expression is the occurrence of a line of slightly taller trees in a well-forested area (Hough, 1960). The same increase in availability of water allows these trees to grow a little taller than their neighbors, and although such a difference may not be particularly obvious, it is often distinguishable.

Another type of fracture trace is the soil tonal change and alignment, particularly in an area that has been extensively planted with crops where the occurrence of vegetation and its patterns has been determined by man. Careful examination of the areas may reveal very subtle changes in the tone of the soil or of the crops themselves. Larger water content of the soil is expressed on the photographs by a relatively dark zone which allows otherwise insignificant differences in moisture to be seen.

Still another manner in which fracture traces are indicated on aerial photographs is by broad but very shallow linear depressions in the topography. Mollard (1957) refers to these depressions as microrelief features and describes them as being "50 to 500 feet across, six inches to several feet deep and many hundreds of feet long." The theory of origin of these features attributes them to gradual leaching of the soil by downward percolation of water along a joint or zone of fracture. This photogeological expression of fracture traces and lineaments varies widely among different bedrock types and with different overburden thicknesses. In soluble limestone such as the Edwards Limestone, their expression can be very obvious due to enhancement through solution along the fractures, whereas in most other rock types their expression is more subtle.

Alternative Methods of Analysis

Several investigators have attempted to overcome the contrary, subjective nature of identifying lineaments by utilizing objective interpretive procedures. Trainer (1967) was the first to study lineaments statistically when he proposed an "objective method of investigating the areal abundance of fracture traces (lineaments) seen on aerial photographs." He argued in favor of a "uniform duration of search, in time per unit area," adding that the "rate of discovery of the traces decreases logarithmically with time." Trainer acknowledged concern over the reproducibility of his results, noting that "problems of subjectivity are inherent in the interpretation of aerial photographs." He also observed that it "is impossible to find all the fracture traces on a given image in a practical period of time."

A different approach to the problem was proposed by Podwysocki *et al.* (1975). These investigators sought to minimize or eliminate "the effect of operator variability and subjectivity in lineament mapping" by use of several machine processing methods. They compared independent interpretations of an MSS band 5 Landsat image by four observers and related these results to those of another group. After analyzing the results, a "large amount of variability" in both the number and length of linear features was found.

Podwysocki and his colleagues then attempted to use two machine-aided mapping techniques to simulate directional filters: (1) an edge-enhancement algorithm and (2) a "television (analog) scanning of an image transparency which superimposes the original image with one offset in the direction of the scan line." Although these methods created similar products, they were found to introduce processing artifacts that were mistaken for lineaments. Moreover, both methods still relied on an interpreter to detect and analyze linear features within the image so that even if the image had been faithfully enhanced, the presumed subjectivity of the interpretation would not be eliminated. The same conclusion is also applicable to most other automatic processing systems for mapping lineaments if they require decisions by interpreters after image enhancement is completed (Maffi & Marchesini, 1964; Robinson & Carroll, 1977; and McGuire & Gallagher, 1979).

Other investigators used elaborate methods for evaluating the reproducibility of lineament interpretations. Burns *et al.* (1976) defined coefficients of reproducibility among populations of lineaments; they stipulated that the lineaments must have unit width based on pixel size. Burns and Brown (1978) refined this procedure by measuring reproducibility of digitized lineaments on a pixel--by--pixel basis. Huntington and Raiche (1978) described the degree of correlation or similarity among lineament interpretations stated in terms of the lineaments' "primary characteristics": (1) location, (2) orientation, (3) length, and (4) curvature. A drawback common to all of these procedures is extensive mathematical manipulation of the lineament data. Furthermore, the tests served only to check the relative agreement among multiple interpretations of a single image.

Still other researchers have had mixed success in their efforts to develop an accurate, practical means of perceiving and analyzing lineaments. These have included: use of photos of side-illuminated raised plastic relief maps to enhance linear topography (Wise, 1969); use of transmitted rather than reflected light to view an image (Lattman, 1958); enhancement of satellite images by rotational photographic exposure of unexposed negative film through overlaid positive and negative transparencies (Lawton & Palmer, 1978); and the use of quantitative and predictive geological spatial analysis techniques coupled with digital elevation models to discern topographic lineaments (Eliason & Thiessen, 1986).

Yet, none of these methods have been proven to accurately identify true structural lineaments on the surface of the earth without the aid of a human interpreter. Consequently, photo-interpretation of aerial photographs, despite its inherent subjectivity, remains the most effective procedure for identifying lineaments and fracture traces in conjunction with groundwater-resource investigations.

C) Relation of Lineaments to Groundwater Flow

The most important aspect of fracture traces and lineaments from a hydrogeological viewpoint is the discontinuity in the underlying bedrock associated with the features. Many rock types are almost impermeable when the rock exists as a continuous mass. Therefore, it may be difficult or even impossible to obtain an adequate supply of groundwater in an area underlain by a continuous bedrock mass. However, wells drilled in the same bedrock that intersect natural discontinuities have the potential to provide an adequate water supply for many purposes.

The fractures in the rock associated with the fracture traces and lineaments provide the primary locations for the storage and transmission of groundwater. This is particularly true in relatively impervious igneous, metamorphic and limestone rocks that do not contain a significant amount of internal pore space. Therefore, the ability to obtain an adequate yield in a water well drilled in impervious rock generally depends on intersecting one or more fractures that provide the conduit necessary storage and transmission of groundwater.

Because fracture traces and lineaments are commonly straight in plan view and unaffected by local topographic relief, these features are considered to be surface manifestations of vertical or near-vertical zones of fracture concentration. Such zones of fracturing are capable of transmitting larger quantities of water than the adjacent less-fractured bedrock. The location, orientation, and extent of lineaments can therefore be used to remotely locate zones of high permeability in the aquifer, and areas of high recharge potential in the unsaturated zone of the aquifer. The increase of groundwater circulation along faults, fractures, and joints leads to greater dissolution of the limestone which increases the size of the subsurface features allowing an even greater amount of water to penetrate the formation.

The probability of wells intersecting one or more fractures is increased if the wells are drilled at the intersection of fracture traces or lineaments. This enhanced potential is probably related to two factors. First, a concentration of subsurface rock fractures is believed to occur at the intersection of two linear features. Second, the prospect of the wells intersecting an essentially vertical subsurface fracture is increased when the wells are located at the intersection of two linear features. However, because the subsurface fractures associated with linear features are generally close to vertical, a well drilled along a single linear feature may fail to intersect a fracture and, thus, the well will probably have a small yield that causes it to be unsatisfactory for the drilled purpose.

Caves

Since caves are typically formed by dissolution of limestone by groundwater, another approach to understanding and verifying groundwater development and its relation to lineaments would be to study cave locations with respect to zones of fracturing for a given area. Wilson (1977) verified that mappable structural features have been the primary influence in the localization of dissolved rock in the Cumberland Plateau of northeast Alabama. Because zones of fracturing are known to be associated with increased permeability and solubility, the concentration of springs and caves is believed to be greater along faults and joints and their intersections. He compared the location of caves to lineaments visible on aerial photographs and satellite imagery of the area and found that 115 of 149 caves in the study area lie along lineaments. He found that simple caves, those that can be represented in a two-dimensional plan view with less than 100 feet (30 meter) vertical dimensions, tend to form along lineaments. Complex caves, caves with multi-level passages, large chambers, and great depth generally form at intersections of lineaments. Other studies relating cave development to zones of fracturing were conducted by Gregg (1974), Palmer (1975), Ogden & Reger (1977), Wermund *et al.* (1978), and Barlow & Ogden (1982).

III. Barton Springs Segment of the Edwards Aquifer

A) Location

The Barton-Springs segment of the Edwards aquifer is an ideal location for an investigation of the feasibility of lineament and fracture-trace analysis. This study focuses on the part of the Edwards (Balcones fault zone) aquifer that lies within northern Hays and southern Travis counties in central Texas, for which Barton Springs is the major discharge point. Physiographically, the Balcones fault zone divides the Edwards Plateau in the west and the Blackland Prairie to the east.

The Edwards aquifer is comprised of massive, highly-fractured limestone that extends over a distance of about 250 miles (400 kilometers) along a narrow, arc-shaped band that crosses southwestern and central Texas. Outcrops of formations which form the Edwards aquifer occur in parts of ten counties from Kinney, near the Rio Grande River, through Uvalde, Medina, Bexar, Comal, Guadalupe, Hays, Travis, Williamson, and Bell counties to the northeast (Figure 2).

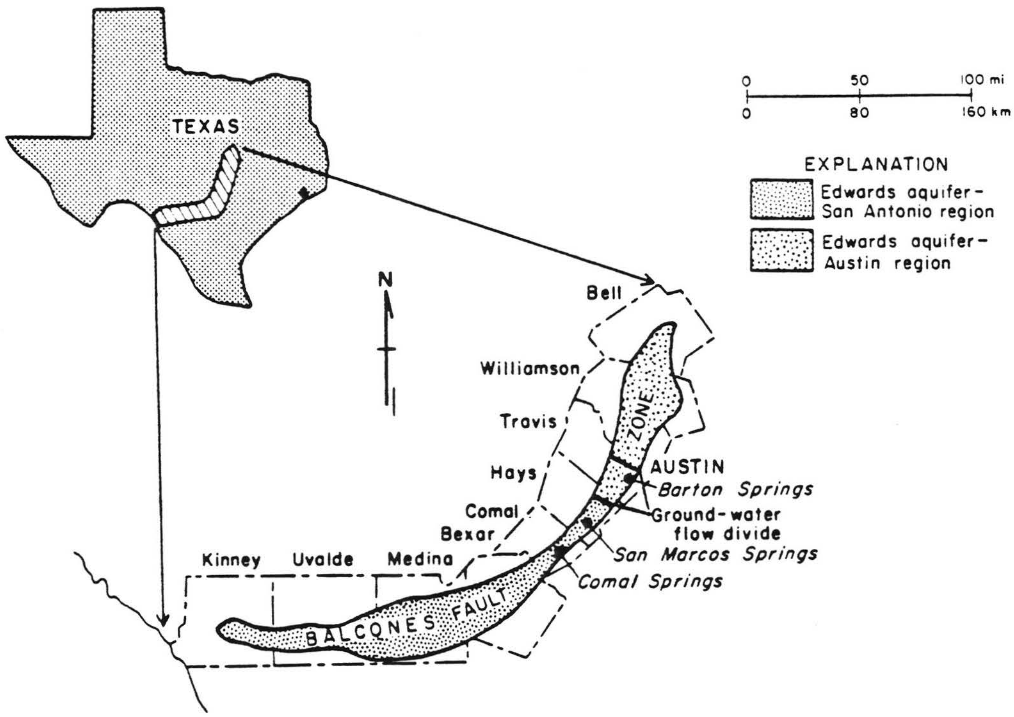


Figure 2: The Edwards aquifer in Texas (from Senger & Kreitler, 1984)

The areal extent of the Barton-Springs segment of the Edwards aquifer is considered to be bounded on the north by Town Lake on the Colorado River, on the west by its contact with the Glen Rose Formation of the Trinity Group and to the east by the dividing line between fresh and saline water (the "badwater zone"). The southern boundary is a hydrologic divide near the City of Kyle that separates the Barton-Springs segment of the Edwards aquifer from the San Antonio segment. The study area covers about 155 square miles (401 kilometers^2), with most of the northern third of the area generally developed and

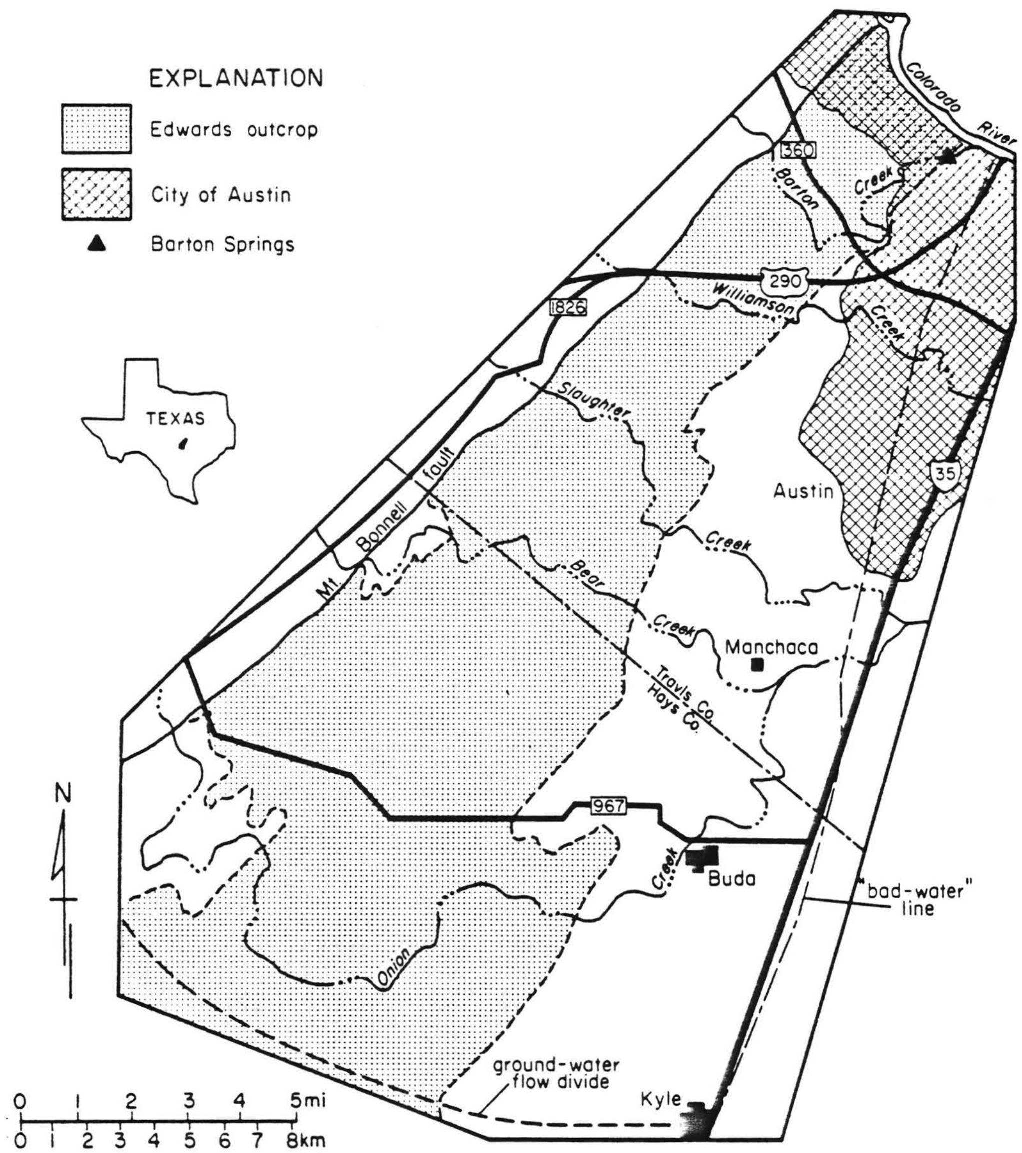


Figure 3: The study area (from Senger & Kreitler, 1984)

urbanized as part of the City of Austin and several outlying communities. Figure 3 identifies the boundaries of the Barton-Springs segment of the Edwards aquifer as delineated for purposes of this study.

The Edwards aquifer is one of the most critical water resources in the state of Texas due to its large usage, large yields, and good water quality. Much of the aquifer lies along the Interstate 35 growth corridor where easily accessible water is especially conducive to expansion at the rural-urban fringe. The Barton Springs/Edwards Aquifer Conservation District (BS/EACD) was created in 1987 to protect the Edwards aquifer which feeds Barton Springs, and is the sole source of drinking water for thousands of people residing within a 255-square mile area that includes parts of Travis, Hays, Bastrop, and Caldwell counties.

In 1989, the approximate annual permitted pumpage for water suppliers was over one billion gallons (BS/EACD, 1990). The aquifer provides good-quality water which generally requires only chlorination as treatment prior to delivery. Withdrawals from the aquifer also provide water for industrial, commercial, and agricultural users. These demands for water are projected to increase as the regional population continues to grow and expand.

B) Geology

Stratigraphy

In the study area, the Edwards aquifer is comprised of the Georgetown Limestone and the underlying Edwards Limestone, both of

Cretaceous age (Figure 4). The Georgetown Limestone ranges in thickness from 40 to 60 feet (12 to 18 meters) in the subsurface, and consists of thin interbeds of fossiliferous and marly limestones. The Edwards Limestone ranges in thickness from about 300 to 400 feet (91 to

Age	Formation	Hydrogeologic Unit
Cretaceous	Buda Limestone	Upper Confining Bed
	Del Rio Clay	
	Georgetown Limestone	Edwards Aquifer
	Edwards Limestone	
	Walnut Formation	Lower Confining Bed
	Glen Rose Limestone	Aquifer

Figure 4: Generalized hydrogeologic column (from Slagle *et al.*, 1986)

122 meters) where not weathered, and is composed of thick to thin-bedded rudist limestone, dolomite, nodular chert, and solution collapse breccias that create cavernous secondary porosity (Slagle *et al.*, 1986).

The Del Rio Clay forms an upper confining layer of the Edwards aquifer, and is composed of a calcareous, fossiliferous clay that is 60 to 75 feet (18 to 23 meters) thick in the subsurface. The Buda Limestone, stratigraphically above the Del Rio Clay, consists of an upper hard, resistant, shell-fragment limestone and a lower marly, nodular, less-resistant limestone (Slagle *et al.*, 1986). Neither formation is known to yield water in the study area (Slade *et al.*, 1985).

The Walnut Formation, which underlies the base of the aquifer, is as much as 60 feet (18 meters) thick, and is composed of a fossiliferous limestone and layers of marl and nodular limestone. The Walnut yields little or no water in the study area and is believed to confine water within the Edwards aquifer. The Glen Rose Formation, stratigraphically below the Walnut, ranges in thickness from 500 to 900 feet (150 to 275 meters) and consists of alternating beds of limestone, dolomite, and marl. The dolomitic members of the Glen Rose are minor aquifers that locally supply small amounts of water containing relatively large sulfate concentrations (Senger & Kreitler, 1984).

Structural Geology

The large productivity of the Edwards aquifer is a result of early Cretaceous and late Cenozoic karstification, which has been enhanced along fractures and Miocene-age faults (Sharp, 1990). The Cretaceous strata of central Texas dip to the southeast perpendicular to the trend of the Balcones fault zone. The beds on the Edwards Plateau are near horizontal with dips of 10 feet per mile. East of the Balcones fault, the dip becomes more pronounced--approximately 100 feet per mile (McReynolds, 1958). According to Muehlberger & Kurie (1956), the regional dip is thought to be the consequence of three geologic processes:

(1) initial dip towards the Gulf of Mexico; (2) subsidence of the basin of the Gulf of Mexico; and (3) uplift of the Edwards Plateau.

***a)** Faults*

The study area lies along the Balcones fault zone southwest of Austin, Texas. The Balcones fault zone is a series of northeast trending, dip-slip, normal faults which displaces gently, eastward-dipping Cretaceous rocks in this area (Senger & Kreitler, 1984). The Mt. Bonnell Fault is the largest fault in the region and forms the western boundary of the study area. Most of the tectonic events responsible for this fault displacement probably occurred during the Miocene epoch. Tectonism is no longer active along this trend.

The formation of the Balcones fault zone is a result of a deeply buried relict structure. The Ouachita orogen lies beneath the area and forms a hinge between the stable continental interior and the subsiding Gulf of Mexico Basin (Clark, 1982). Adjustments across this hinge were probably responsible for the dip-slip dislocations of the Balcones fault system and the majority of joints along the fault zone that have propagated upward from the underlying stress. The overall northeast-southwest trend of the Ouachita orogen is the major determining factor in the orientation of the main bounding faults of the Balcones fault zone system.

The Mt. Bonnell Fault is the westernmost major fracture in the Balcones fault zone in Travis and Hays counties. The fault forms a topographic and structural divide between the Edwards Plateau to the northwest and the Gulf Coastal Plain to the southeast. Striking N 40° - 44° E, the fault can be traced from Hays County, through the community of Oak Hill, and then to a point north of Tom Miller Dam in central Travis County.

Regional extensional stress existing in the rocks of the Gulf Coast geosyncline has caused faulting along a zone of underlying crustal weakness. Dip-slip movement on the Mt. Bonnell Fault has dropped the upper Edwards into contact with the Glen Rose Limestone. At least 160 feet (49 meters) of throw is transferred from the Mt. Bonnell Fault to the southeast by en echelon left faults, which breaks the downthrown block into a series of grabens and horsts (Balke, 1958). The Balcones fault zone and Luling-Mexia graben conforms to this type of stress system, having a minimum stress direction of N 50° W and near horizontal, maximum stress vertical, and an intermediate stress direction of N 40° E and near horizontal (Dunaway, 1962). Consequently, fractures in the Balcones fault zone have an average strike of N 40° E.

b) Joints

Based on 3233 measurements of joint orientations in central Travis County, Dunaway (1962) found 30 percent lie within an azimuth of 30° - 60°. A secondary peak of 21 percent of the joints lie within an azimuth 120° - 150°, a trend roughly perpendicular to the prevailing structural grain in the study area. Specifically, joints in the Edwards

Limestone of the downthrown block strike in two prominent directions: N 48° E and N 42° W (Dunaway, 1962). The N 48° E striking joints are tension joints related to the Mt. Bonnell Fault and transverse jointing of the Colorado syncline. The N 42° W striking tension set is probably the result of flexing parallel to the direction throw is transferred from the Mt. Bonnell Fault to the southeast by en echelon faulting. A minor N 10° W striking tension set is probably related to the N 10° W striking joints located west of the fault (Balke, 1958). As observed by Muehlberger & Kurie (1956) and Dunaway (1962), an overwhelming number of joints had vertical or near-vertical dips.

C) Hydrology

A typical cavernous or karstic aquifer is exemplified by extremely large permeability but low overall porosity. Irregular dissolution of the limestones comprising the Edwards aquifer has created secondary porosity which greatly affects the hydraulic properties of the aquifer. As a result, the aquifer is extremely anisotropic. Significant porosity along particular bedding planes was created through dissolution by meteoric water during an interval of subaerial exposure at the close of the Edwards Limestone period of deposition (Abbott, 1977a). Vertical zones of greater porosity are a result of steep-angle normal faulting that began during the Miocene Epoch (Senger & Kreitler, 1984). At outcrops, these zones allow surface water to readily enter and move through the unsaturated zone to the water table.

Extensive faulting, both at the outcrop and throughout the formation, is an important feature of the Edwards. It creates variations in the physical characteristics and dimensions of the aquifer and provides conveyance pathways for surface-water infiltration and groundwater movement, both of which enhance solution cavity development. Consequently, well yields vary tremendously over short distances.

A narrow portion of the Edwards aquifer extending along most of the eastern boundary is overlain by the Del Rio Clay, a relatively impermeable formation that functions as a confining layer for groundwater within the underlying aquifer (21 percent of study area). Wells in the study area having the largest yields produce from this confined section, where the wells penetrate the total thickness of the Edwards. In the area west of this confining layer, particularly where the formations of the aquifer crop out, the groundwater in the study area is considered to be generally under free-surface, water table conditions (79 percent of study area).

Groundwater movement within the Barton-Springs segment of the Edwards aquifer is from the southwestern and western portions of the aquifer eastward and northeastward, toward Barton Springs on the lower reach of Barton Creek (Figure 5). Historically, hydraulic gradients of the potentiometric surface have ranged from less than 20 to 200 feet per mile. It is estimated that, under "normal" conditions, the bulk of water recharged at Onion Creek would move through the aquifer for

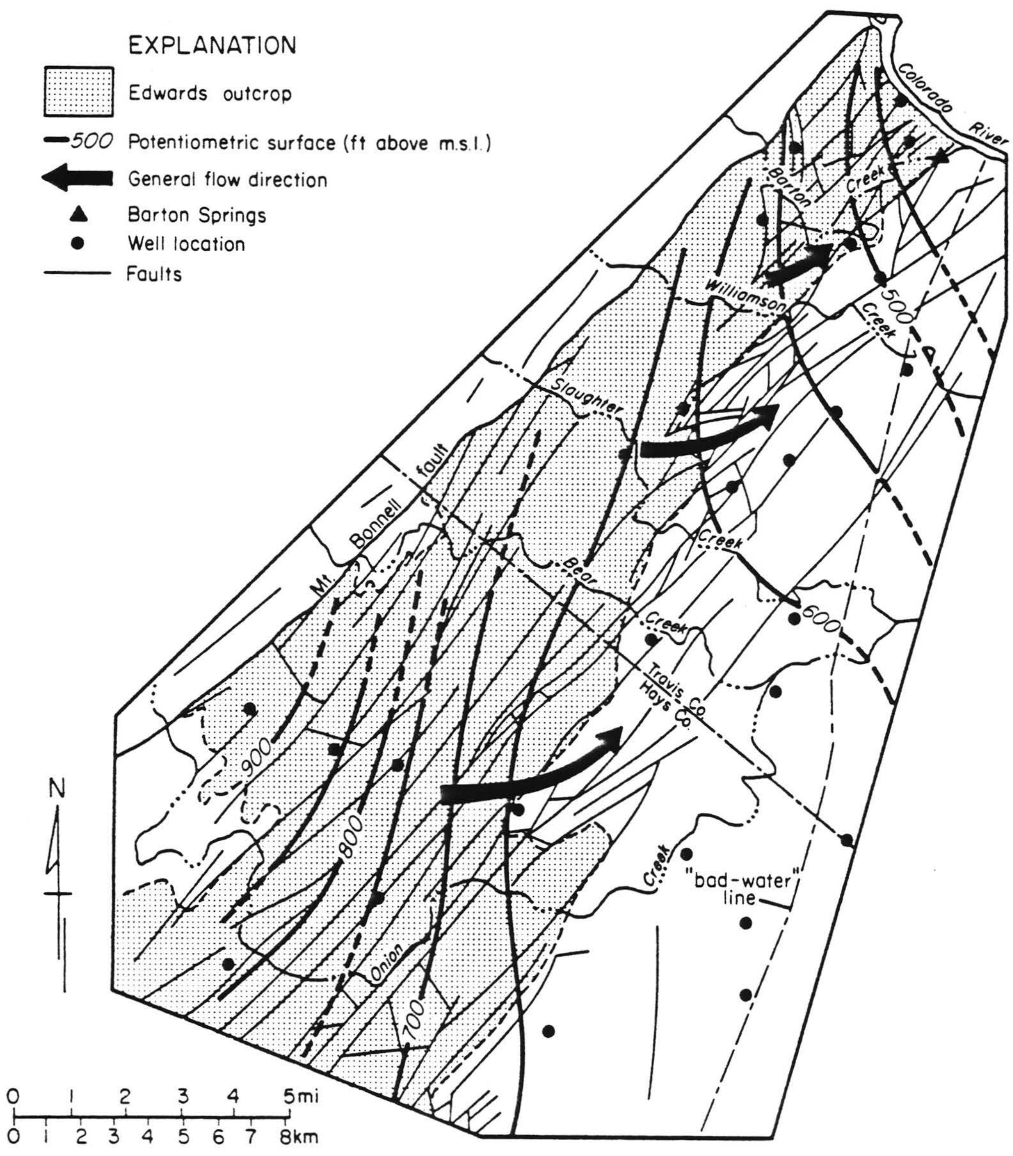


Figure 5: Generalized groundwater flow in the study area (from Slade *et al.*, 1985)

about 3 to 5 years before being discharged through Barton Springs.

Barton Springs, located in Zilker Park near the center of Austin, has an average discharge rate of about 50 cubic feet per second (1.4 m^3/second) and is currently the fourth largest spring in Texas (BS/EACD, 1990). The minimum discharge was measured in 1956 at a flow rate of 10 cfs (0.3 m^3/second). According to Slade *et al.* (1986), the maximum discharge is 166 cfs (4.7 m^3/second). The springs serve as one of the sources of municipal water for the City of Austin's Green Water Treatment Plant on Town Lake. On the average, about 90 percent of the total discharge from the the Barton-Springs segment of the Edwards aquifer occurs through Barton Springs and other associated springs in the immediate vicinity (36,200 acre-feet per year), with the remainder being pumped from wells throughout the aquifer for water supply purposes (BS/EACD, 1990).

Recharge

The Barton-Springs segment of the Edwards aquifer is recharged primarily by infiltration of surface runoff during storm events into fractures and other openings in the outcrop area of the Edwards and Georgetown Limestones, principally along water courses and streambeds. Creek water entering the recharge zone from the west infiltrates through faults and fractures along the creeks within the recharge zone. Studies by the U. S. Geological Survey (Slade, 1984) show that approximately 85 percent of the recharge into the Edwards in the

Austin area occurs in the main channels of Barton, Williamson, Slaughter, Bear, Little Bear, and Onion creeks. Groundwater flow within the Barton-Springs segment of the Edwards aquifer can be summarized as follows:

1) Recharge occurs through fractures along major streams
2) Once in the aquifer, groundwater is channeled northeastward due to the predominance of northeast trending faults and fractures
3) Groundwater discharges at Barton Springs along vertical faults

Anisotropic Groundwater Flow

Groundwater flow in karst aquifers is very different from flow in granular aquifers. In general, the slow, dispersive, laminar flow assumed by Darcy's Law are seldom in evidence in karst terranes. Most groundwater flow in karstic aquifers like the Edwards is likely to be very rapid, convergent, and turbulent within discrete conduits (Smart & Hobbs, 1986). In fractured rock, groundwater movement is controlled by the distribution, interconnection and orientation of joints, faults, and bedding planes. The zone of saturation consists of these water bearing discontinuities separated by masses of solid rock having relatively much lower permeability (Meiser & Earl, 1982). These fractured aquifers are therefore strongly heterogeneous and anisotropic. Some aspects of fracture flow are:

- Irregular, elongate cones of depression produced by wells pumping within fracture zones cause anomalous drawdowns in observation wells. In limestone aquifers, recorded drawdowns of several meters in observation wells 1000 - 2000 feet (305 - 610 meters) away along fracture zones are not uncommon, while very little drawdown has been noted in nearby observation wells in unfractured bedrock (Meiser & Earl, 1982).

- Wells pumping in fracture zones can interfere dramatically with each other when located in the same fracture system; these effects must be addressed when evaluating the sustained yield potential of wells related by obvious fracture traces.
- The total recharge area is virtually impossible to define accurately for wells in major fracture zones. Pollutants can travel tremendous distances from sources that are not readily apparent.
- Groundwater flow rates along well-developed fracture zones are commonly orders of magnitude greater than flow in poorly-jointed, dense bedrock. This factor must be considered when locating monitoring wells and interpreting data for waste disposal, mining, or other activities affecting groundwater chemistry.
- Fracture zone conduits perpendicular to strike of bedding can produce a step-like pattern of groundwater movement in a general downgradient direction. Therefore, strict interpretation of flow normal to "water table" contours tends to oversimplify the complex path of actual groundwater flow.

- Groundwater flow in a bedrock fracture zone may vary considerably in the vertical dimension with respect to lithologic changes. For example, a sequence of shale with interbedded sandstones frequently shows larger well yields in the cleanly fractures sandstones than in the denser shales where joint openings tend to be tight (Meiser & Earl, 1982).

Karst aquifers are very vulnerable to the effects of chemical spills because of the unique geologic features associated with karst terranes (Field, 1989). Sinkhole development and a lack of recognition of karst hydrological principles can allow chemical contaminants to rapidly infiltrate into the subsurface environment. Vadose storage and flow to phreatic conduits tend to concentrate contaminants for discharge at relatively few points. It is this ability to store and transmit large quantities of highly concentrated chemical contaminants to select discharge points that makes karst aquifers extremely sensitive to the effects of chemical spills. This unusual form of chemical transport and storage leads to very serious threats to human health and the environment. Thus, the ability to identify discrete groundwater flow paths by using lineament analysis will allow the water resource manager to predict groundwater plume migration and subsequent mitigation applications.

D) Water Chemistry

The quality of water from the Edwards aquifer varies throughout the BS/EACD area. In general, the chemical composition in the aquifer grades downdip from a calcium magnesium/bicarbonate water in the recharge area to a sodium sulfate water and finally to a sodium chloride water deep within the basin (Senger & Kreitler, 1984). This increase in mineralization of the groundwater downdip may be due to intensive faulting which creates numerous barriers to groundwater movement in an easterly direction. In addition to mineralization, the Slade, *et al.* (1986) reports that poorer quality water in the Glen Rose Limestone may be leaking into the Edwards aquifer, increasing its sulfate and strontium concentrations. Leakage is thought to be associated with large fault displacements, which bring the Edwards Limestone into contact with the Glen Rose Limestone updip. In general, the largest displacements occur along the Mt. Bonnell Fault and in the eastern part of the study area in Hays County and southeastern Travis County.

The badwater line, which forms the eastern boundary of the study area, represents a relatively stable hydrochemical boundary separating the two distinct zones of the Edwards aquifer. In the saline "badwater zone," conditions are reducing, as evidenced by the odor of hydrogen sulfide, and the water contains 1000 mg/L to more than 10,000 mg/L of dissolved solids (Clement, 1989). The occurrence of NaCl-type water is related to abundant faults, which create pathways for deep basinal brines and restrict recharge of fresh groundwater from the west. Prezbindowski

(1981) explained the water chemistry as being controlled by two processes: (1) mixing of fresh water from the Edwards aquifer moving downdip into the basin with deep saline waters moving up and out of the basin; and (2) dissolution of the Edwards Limestone by undersaturated groundwater moving downdip. A detailed discussion of the badwater zone geochemistry is provided by Clement (1989).

IV. Methods of Data Analysis

A) Lineament Analysis

Determination of Lineaments

Lineaments have been mapped in the study area by C. M. Woodruff, Jr., Fred Snyder, and Albert E. Ogden. These lineament maps were used by De La Garza and Slade (1986a) in a previous lineament study and are available from the City of Austin's Department of Environmental Protection. The lineaments were interpreted from mosaics of 1:20,000 black-and-white aerial photographs taken in 1937 by Tobin Aerial Research, Inc. of San Antonio. Each of the mosaics were viewed individually for two 20-minute sessions by each interpreter for a total of 120 minutes of viewing time for each 7.5-minute quadrangle. In order for a linear feature to be mapped, a minimum length of a 1.25 cm (300 meters on the ground) was established. Those lineaments confirmed as natural features were transferred to U. S. Geological Survey topographic maps.

During the transfer process from the aerial photographs, errors in lineament orientation are likely to be introduced. Dix and Jackson (1981) assessed the magnitude of these errors in pilot studies on two 7.5-minute quadrangles. Lineaments were transferred onto 1:24,000 topographic sheets and their orientations checked against those on the original photographs. Differences between lineament azimuths on the mosaics and topographic maps lie between 0° and 10°, with a mean of 5°. Because lineaments in this study were grouped into 10° sectors for subsequent analysis, these errors are unlikely to affect the results of the analysis.

After the lineament maps were obtained, the endpoints of each linear feature were digitized and a unique identification label was assigned to each of the 938 lineaments and fracture traces identified in the study area (Figure 6). Each identification label also indicated whether the lineament had been identified by two of the three interpreters or by all three observers. One hundred and thirty-six lineaments were identified as "two-man" and 48 were identified as "three-man" lineaments. A FORTRAN program was written to determine the length and azimuth of each lineament, based on the locations of the end points. The statistical tabulation of the lineaments, computed using a program listed in Press *et al.*, (1986), is shown in Table 1. The lineament length data was evaluated for the statistical parameters of deviation, variance, skewness, and kurtosis. The method of interpretation of these parameters is not to attach a significance to each statistical value, but is used in comparison with other samples. For example, the sample having the largest variance or standard deviation, consequently, has the

Figure 6: Location of lineaments in the study area (detailed lineament map is included in map pocket)

largest distribution among the values of the observations, provided all the measurements are made in the same units.

Statistical Analysis

The lengths and orientations of lineaments in the study area were processed in order to identify preferred orientations (peaks) and to test whether these peaks are statistically significant and, therefore, geologically meaningful. Lineament and fracture trace azimuths were divided into 18 10° sectors. Then, the total lineament length in each

AZIMUTH STATISTICS	
Maximum:	179.9°
Minimum:	0.7°
Arithmetic Mean:	39.9°

LENGTH STATISTICS	
Maximum:	5332.9 m
Minimum:	310.7 m
Arithmetic Mean:	1096.0 m
Average Deviation:	463.3 m
Standard Deviation:	639.0 m
Variance:	408317.5 m^2
Skewness:	1.9
Kurtosis:	5.2

Table 1: Summary of selected statistics for azimuths and lengths of digitized

sector (L_s) was calculated and summed for the overall total lineament length (L_t). The relative length (L_r) was determined by:

$$L_r = \frac{L_s}{L_t} \qquad (1)$$

Next, the length-weighted frequency (**F**) of the azimuth data was calculated. As described by Dix & Jackson (1981), this parameter expresses the total lineament length in a 10°-wide sector of the graph, weighted in proportion to the number of lineaments (**n**) in the area in question:

$$F = \frac{L_s \times n}{L_t} \qquad (2)$$

Length-weighted frequency is used to combine lineament length and number of lineaments into a single parameter (Baumgardner, 1987). The advantage in using this measure is that values from different areas can be compared while allowing differences in number of lineaments in each area.

For this study, a peak is defined as any 10°-wide sector with a magnitude larger than the average for that graph. The "peakedness" of a graph is affected by the number of lineaments in the sample. Dix and Jackson (1981) devised a measure of peakedness called the index of preferred orientation (**IPO**):

$$IPO = \frac{\sum_{i=1}^{18} |L_r - 0.05| \times 100}{1.8} \qquad (3)$$

They observed that values of **IPO** for computer-generated, geologically meaningless, random "lineaments" decreased as sample size increased. The decrease in value was rapid from 50 to 200 lineaments but slowed as the number of lineaments increased above 200. As a result, Dix and Jackson (1981) proposed that data sets should contain at least 200 lineaments to "minimize the effects of randomly oriented lineaments on geologically significant trends."

To determine which greater-than-average peaks were significant, a chi-square test was used to measure the difference between each peak and the mean **F** value (Siegel, 1956). The χ^2 technique tests whether the observed frequencies are sufficiently close to the expected ones to be likely to have occurred under the null hypothesis. Dix and Jackson (1981) concluded that the 99-percent confidence level (p = 0.01 level) should be used to define geologically meaningful peaks because none of their samples with more than 100 computer-generated "lineaments" had significant peaks at that level. Because a circular-normal distribution cannot be assumed, the χ^2 one-sample nonparametric test was applied. This test requires the use of lineament frequency rather than magnitude. To accommodate this requirement, the length-weighted frequencies were used as follows:

$$\chi^2 = \sum_{i=1}^{k} \frac{(\mathbf{F} - \overline{\mathbf{F}})^2}{\overline{\mathbf{F}}} \tag{4}$$

where $\overline{\mathbf{F}}$ = arithmetic mean of length-weighted frequency

In general, the larger χ^2, the more likely it is that the observed frequencies did not come from the population on which the null hypothesis is based.

By dividing the χ^2 value for each peak by the degrees of freedom (υ = **k** - 1, where **k** equals the number of 10° sectors forming the peak), the Bernshtein accuracy criterion, **H**, was determined (Vistelius, 1966):

$$H = \frac{\chi^2}{\upsilon} \tag{5}$$

This parameter serves as a check on the actual existence of a preferred orientation. If **H** ≥ 2, then it can be presumed that the initial hypothesis is not consistent with the observations. With **H** ≤ 2, the initial hypothesis is not contradicted by the observed distribution.

B) Well Analysis

Productivity of Water Wells

The yield of a well may be expressed in terms of its specific capacity which is defined as the yield in gpm/ft of drawdown for a stated pumping period and rate. The specific capacity of a well is affected by the hydraulic properties of the aquifer (particularly the coefficients of transmissivity and storage), by the radius of the well, the pumping period, and the depth of saturated rock penetrated by the open section of the well bore (Siddiqui, 1969). The transmissivity of the aquifer has the greatest influence on the specific-capacity value of a well; as this increases so does specific capacity. However, the specific capacity of a well cannot be an exact criterion of the coefficient of transmissivity because specific capacity is often affected by storativity, partial penetration, well loss, well diameter, and hydrologic boundaries (Walton, 1988). In most cases these factors adversely affect specific-capacity values and the actual coefficient of transmissivity is greater than the value computed from specific-capacity data. Nevertheless, specific capacity is a valuable measure of the productivity of a well.

Collection of Well Data

In order to examine the relation between productivity of water wells and proximity to lineaments, the specific capacities of 27 wells in the study area were obtained. This data was acquired from several sources. Four of the specific-capacity values are the results of specific hydrogeologic investigations completed on wells in the study area. Due to the scarcity of pump-test data in the Edwards, these four studies provide critical information about the hydraulic properties in the aquifer and are summarized in detail in Appendix A.

During the field investigations, six other specific-capacity values were determined. A 300-foot (91 meter) long electric probe (e-line) was utilized to determine the water level in the well. After measuring the static water level, the pump was energized and the subsequent drop in the water level was measured with the e-line. When the water level reached equilibrium (typically 15 - 45 minutes in the Edwards), the discharge was measured using a flow meter. The specific-capacity value was calculated as the drawdown in feet divided by the discharge in gallons per minute.

Unfortunately, several problems were encountered during the collection of field data. Many wells do not have an adequate access port at the wellhead for the e-line probe. In addition, due to the depth to water in the wells (typically 175 - 250 feet) and the poor condition of the wells in general, obstructions in the wellbore were frequently encountered in several wells. Three wells had pumping water levels deeper than 300 feet which prevented the drawdown measurement.

Specific capacities for two wells were determined using a permanently installed airline. This line, typically $\frac{1}{8}$ inch (0.3 cm) in diameter, ran down the length of the well to the depth of the pump. The line was pressurized by either a compressor or a hand pump and the initial pressure reading in pounds per square inch was recorded. The pressure meter measured the amount of pressure at the pump caused by the column of water in the well. After the pump was activated, the resulting drop in the water level is reflected by a corresponding drop in the airline pressure. The difference in pressure between the static water level and the pumping water level was used to calculate the drawdown by using the relationship of 2.31 feet (0.7 meters) of drawdown to one pound of pressure.

Historical data from either prior pump tests or drilling logs was used for the remainder of the specific capacities. Data derived from pump tests is more reliable because discharge and drawdown measurements are made over time. Drilling logs from all located and plotted wells in the study area were reviewed at the Texas Water Development Board's Central Records office. In the Edwards aquifer, the overwhelming number of wells do not have reliable discharge and drawdown data. According to a local driller, Byron Benoit of Associated Drilling in Manchaca, Texas, most well yields on new wells drilled in the Edwards are estimated by air-jetting. Thus, in the karstic and faulted Edwards, much of the air and water is blown into solution cavities along the wellbore. In addition, using data gathered from driller's logs is not as reliable because it is not known whether or not steady-state conditions existed before water-level declines were measured. Occasionally, however, discharge and drawdown measurements are collected during drilling procedures and can be used as a indicator of the relative productivity of a well. Well locations, specific capacities, and the method of determination are tabulated in Table 2.

Several researchers (Brook *et al.*, 1984) propose normalizing specific-capacity data in order to accurately compare values between different studies. Lattman and Parizek (1964) recommend that the specific-capacity values be divided by the total depth of saturated rock penetrated by each well to obtain what LaRiccia and Rauch (1977) designate as the specific-capacity index. However, due to the extreme vertical faulting of the Edwards aquifer, the thickness and water levels are highly variable. In addition, further manipulation of the basic specific-capacity data reduces the viability of the data due to contrived

Table 2: Specific-capacity data tabulated for wells in the study area

Well Number	Owner	Latitude (ddmmss)	Longitude (ddmmss)	Date of Test	Discharge (gpm)	Drawdown (feet)	Method
58-42-812	W. F. Guyton & Assoc.	301554	974847	Jun-69	20.00	1.50	S
58-42-821	Trigg-Forister Bldg.	301540	974838	Feb-82	16.00	10.40	P
58-42-8M	Allen Keller Co.	301533	974747	Jun-79	100.00	60.00	S
58-42-8S	Espey Huston & Assoc.	301618	974908	Apr-82	150.00	6.00	D
58-49-9H	Charles Ranch	300933	975354	Aug-87	287.00	138.00	D
58-50-223	City of Sunset Valley	301339	974835	Jun-90	125.00	49.65	A
58-50-414	Lee V. Johnson	301047	975027	Nov-86	51.00	18.00	D
58-50-704	Marbridge Found. #5	300812	975120	Feb-68	1150.00	31.00	S
58-50-731	Shady Hollow Estates	300858	975136	May-83	210.00	10.00	P
58-50-830	Slaughter Cr. Acres	300937	974904	Aug-71	45.00	160.00	S
58-50-835	Onion Creek CC	300845	974845	May-69	270.00	12.00	S
58-50-8A	Native Texas Nursery	300915	974915	Jul-90	36.00	118.96	P
58-57-307	Dahlstrom Middle Sch.	300559	975256	May-90	68.00	18.34	E
58-57-910	Mt. City Oaks WSC	300205	975357	Jul-90	184.00	0.25	E
58-58-102	Cimarron Park #2	300622	975115	Apr-84	600.00	4.00	P
58-58-115	Estate Utilities WSC	300723	975219	Nov-79	660.00	12.00	S
58-58-123	Elizabeth Porter	300634	975030	Feb-85	400.00	15.00	D
58-58-1A	Frank Burdette	300726	975217	Jun-90	10.75	0.29	E
58-58-1B	Hays Hills Baptist Ch.	300702	975228	Jun-90	71.00	7.00	P
58-58-1EE	Neptune-Wilkinson	300504	975200	Apr-84	225.00	127.00	D
58-58-202	Mystic Oak WSC #1	300728	974848	unk	42.00	185.00	S
58-58-2E	Hunter Industries	300537	974852	Nov-89	200.00	117.00	P
58-58-406	Texas-Lehigh Cement	300341	975120	Aug-66	1200.00	53.00	D
58-58-412	Plum Creek WSC	300435	975003	Jun-90	470.00	52.60	E
58-58-413	City of Buda #3	300420	975004	Mar-87	430.00	99.33	P
58-58-506	Goforth WSC	300442	974949	Sep-77	310.00	65.00	P
58-58-508	Goforth WSC	300443	974950	Jul-90	227.00	90.90	A

Methods:

E: Field Measurement (E-line)
A: Field Measurement (airline)
D: Data from drillers logs
S: Data from Slade & De La Garza (1986)
P: Data from previous pump tests

assumptions. The inhomogenous, anisotropic nature of the Edwards aquifer prevents the utilization of typical assumptions that could be used to translate specific-capacity data into values of transmissivity or permeability (as in Meyer, 1963) except for site-specific applications.

Statistical Analysis

In order to test for statistical validity of the collected data, the controlling factors must be defined and isolated and their relative importance established. In carbonate or other fractured aquifers, for example, the geologic factors influencing porosity and permeability distribution, and hence the range in well yields, are frequently not known and should be defined. Appropriate statistical techniques may be used to draw conclusions about the population from the evidence provided by the sample data.

First, the distribution of the data sets must be determined. The 27 specific-capacity values collected from the study area range in value over four orders of magnitude. As expected, regression analysis failed to show a Gaussian distribution. The data was also subjected to the Lilliefors Bound Test. At the 95%-confidence level, the specific-capacity data plotted outside of the bounds of normal distribution. This variability in values for specific capacity and distance is illustrated in box diagrams (Figure 7). Consequently, nonparametric or distribution free statistical tests were conducted because the data were not normally distributed.

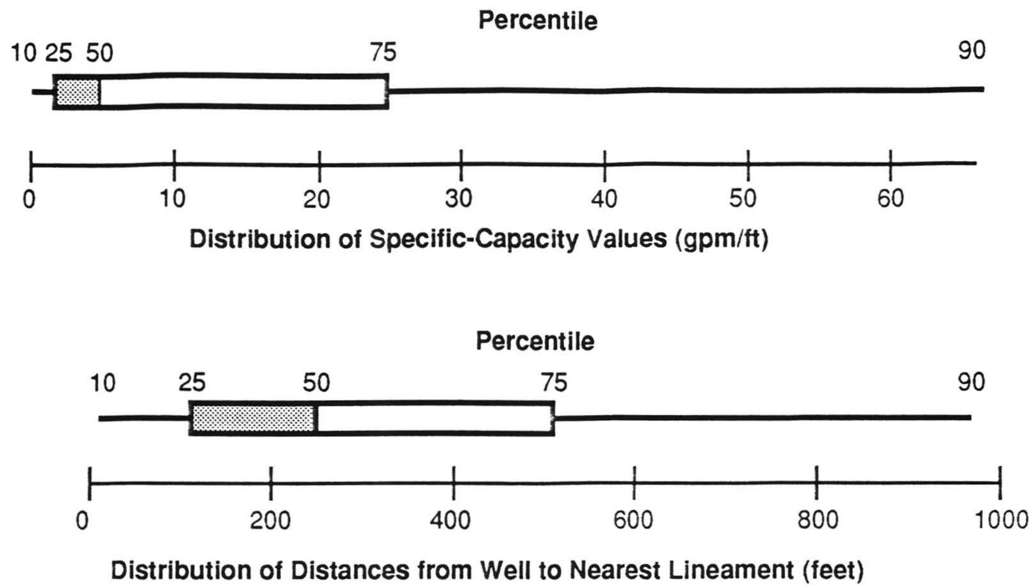


Figure 7: Box diagrams of distribution for values of specific capacities and distances from wells to nearest lineament

Nonparametric statistical tests do not require the use of normally distributed data nor does the shape of the distributions need to be known. Thus, a small number of observations can be used and computations are fairly simple. A further advantage of nonparametric techniques is that they may be used with data that are not exact in any numerical sense, but that in effect are simply ranks. Siegel (1956) presents these techniques and provides examples from behavioral sciences.

The Mann-Whitney U Test is used to test whether two independent samples have been drawn from the same population (Siegel, p. 116). For this study area, it is an ideal technique for determining if the difference between specific capacities of wells located to the southeast of a NE-SW trending lineament are random data or structurally controlled. Thus, the null hypothesis to be tested is: $\mathbf{H_0}$ - direction of a well from a lineament has no effect on specific capacity. The alternative hypothesis is $\mathbf{H_1}$: direction of a well from a lineament has a significant effect on specific capacity. The statistic U used in this test, is calculated by the following equations:

$$U_1 = n_1 n_2 + \frac{1}{2}\,[n_1(n_1 + 1)] - R_1 \qquad (6)$$

$$U_2 = n_1 n_2 + \frac{1}{2}\,[n_2(n_1 + 1)] - R_2 \qquad (7)$$

where $\mathbf{R_1}$ = sum of the ranks assigned to the group whose sample size is n_1; $\mathbf{R_2}$ = sum of the ranks assigned to the group whose sample size is n_2; and $U_1 + U_2 = n_1 n_2$. The smaller of the two values, U_1 and U_2, is the U used in the test. This U value is compared to the theoretical U at a particular significance level. If the probability associated with the observed value of U for the sample sizes n_1 and n_2 is equal to or less than the previously set level of significance α, the null hypothesis is rejected. A detailed explanation with hydrogeological applications of this technique is given by Siddiqui & Parizek (1972).

For this study's sample size, n_1 and n_2, the significance of an observed value of U is determined by referring to Table K in Siegel (1956, p. 276). For a significance level of 0.05 (that is, a 95%-confidence level), the probability associated with the observed value of U is equal to 45. Therefore, if the calculated value of U is less than 45, the null hypothesis is rejected. Table 5 gives the specific-capacity values listed in ascending order of magnitude, direction of the well from the nearest lineament, their ranks, the ranks for the two groups, the sum of these ranks, and the number of observations in the two groups.

C) Water Chemistry

One sample was collected and analyzed from each of 61 wells that extract water from the study area. A basic chemical survey of anions, cations, and carbon species was conducted on these samples in the Department of Geological Sciences laboratories as described in the following sections. Results from the chemical analyses are tabulated in Table 3. In addition, 20 water samples were collected with funding from the Texas Water Development Board. The Lower Colorado River Authority's Environmental Laboratory tested for 34 parameters including radioactivity and total organic carbon. The results are compiled in Appendix B.

Field-Data Collection

The water samples were collected over a two-month period during the summer of 1990. The sampling point was located as close to the wellhead as possible and always before the water flowed through pressure or storage tanks, chlorinators, softeners, or any filtering apparatus. Groundwater was pumped until a constant pH reading was obtained to ensure flushing of the well bore. Three parameters were measured in the field for each sample collected: pH, water temperature, and conductivity.

For this study, the pH and temperature were measured using an Orion Research model SA250 pH meter. The meter was calibrated daily with standard buffers of pH 4 and 7. In most cases, the water was routed through a flow cell to simulate *in-situ* measurements. Because of its critical effect on pH, temperature measurements were recorded simultaneously using the temperature probe of the SA250 pH meter.

Conductivity values were obtained by using a Hach model 44600 Conductivity meter. Values for total-dissolved solids (TDS) were calculated from the concentrations of the major anions and cations of each of the collected samples. Ratios of TDS to conductivity ranged from 0.5 to 0.8 with a mean ratio of 0.66. The probe was rinsed with deionized water after each sample to prevent contamination of subsequent measurements.

At each well, two water samples were collected in nalgene plastic bottles for lab analysis. Both sample bottles were rinsed and filled with filtered water using a 0.45 micron (μ) membrane filter. A 60 milliliter (ml) sample was collected for the carbon and anion analyses. No preservative was added to this sample. For the cation analysis, a 30 ml sample bottle was preserved with 2 drops of nitric acid (HNO_3). All samples bottles were transported on ice and stored in a refrigerator until analysis.

Laboratory Analysis

The amount of dissolved inorganic carbon (DIC) for each sample was determined with a Dohrmann DC-180 Carbon Analyzer. After calibrating the instrument with a 50 ppm carbon standard, 500 microliters (μl) of water sample are injected by syringe. The sample is then delivered to an ultraviolet reactor for oxidation. During an analysis, the non-dispersive infrared CO_2 detector (NDIR) produces electrical output peaks which are integrated and displayed in ppm carbon concentration units.

Using the resulting value of carbon, alkalinity was calculated by multiplying the first ionization constant, (α), by the the corresponding known value of DIC. The ionization constant is calculated as follows:

$$\alpha_1 = \left[\frac{H^+}{K_1} + 1 + \frac{K_2}{H^+}\right]^{-1} \qquad (8)$$

where K_1 is equal to $10^{-6.4}$ and K_2 equals $10^{-10.3}$ at 25° C. However, since the water samples were not collected at 25° C, the equilibrium constants must be adjusted to temperature using this formula:

$$\ln\frac{K_1}{K_2} = \frac{\Delta H^\circ}{R}\left[\frac{1}{T_2} - \frac{1}{T_1}\right] \qquad (9)$$

In this case, temperatures are in degrees Kelvin with $\mathbf{T_2}$ equal to 298° K (25° C) and $\mathbf{T_1}$ is the temperature at the time of collection. The resulting $\mathbf{K_1}$ value is substituted into Equation 8 and used to determine alkalinity. Bicarbonate values were calculated by multiplying alkalinity by the formula weight of HCO_3.

Similar to the carbon analysis, anions in the groundwater were also determined from filtered, unacidified samples. Samples were analyzed using a Waters Ion Chromatograph for the following anions: flouride, chloride, nitrite, bromide, nitrate, phosphate, and sulfate using EPA method A-1000 (proposed). This method utilizes a 150 x 4.6 mm IC-Pak A HC column and a borate/gluconate eluent. Detection was by both conductivity and ultraviolet-absorption methods. High- and low-concentration working standards were interspersed among the water samples to ensure the accuracy of the analysis.

Cations for all samples were determined using a JY-70 inductively-coupled atomic emission plasma spectrometer. Details of this process can be obtained from the instrument manual. Working standards and duplicate samples were interspersed to check calibration of the instrument. Cations analyzed include: aluminium, barium, calcium, chromium, iron, potassium, magnesium, sodium, lead, strontium, and zinc.

The charge-balance error (**E**) for each water sample was calculated using the equation:

$$\mathbf{E} = \frac{\sum \mathbf{zm_c} - \sum \mathbf{zm_a}}{\sum \mathbf{zm_c} + \sum \mathbf{zm_a}} \times 100 \qquad (10)$$

where $\mathbf{z}$ is the ionic valence, $\mathbf{m_c}$ the molality of cation species, and $\mathbf{m_a}$ the molality of anion species.

			Field Data				Carbon Species			Anions		
Well Number	**Owner**	**Date 1990**	**Temp. (°C)**	**pH**	**Cond. (µS)**	**TDS (mg/l)**	**DIC (ppm C)**	**Alkalinity (meq/l)**	**HCO3 (mg/l)**	**Cl (mg/l)**	**NO3 (mg/l)**	**SO4 (mg/l)**
58-58-1A	Frank Burdette	11-Jun	23.6	7.27	552	395	81	5.941	362.41	11.56	6.91	7.72
58-58-115	Estate Utilities WSC	11-Jun	23.6	7.30	528	391	82.35	6.088	371.36	9.76	5.71	5.20
58-58-508	Goforth WSC	12-Jun	25.2	7.30	653	446	64.95	4.802	292.90	10.85	-	118.26
58-58-412	Plum Creek WSC	12-Jun	24.3	7.20	662	452	77.7	5.584	340.64	10.81	0.93	86.60
58-58-102	Cimarron Park WSC	13-Jun	22.4	7.41	477	347	65.49	4.964	302.79	10.90	6.37	21.44
58-58-114	Cimarron Park WSC	13-Jun	22	7.44	518	384	74	5.642	344.14	10.78	8.00	17.42
58-58-117	Twin Oaks Ranch	13-Jun	23.3	7.59	494	351	63.21	4.936	301.11	9.37	0.32	32.55
58-58-407	Texas-Lehigh Cement	13-Jun	24.9	7.59	661	449	73.57	5.745	350.47	10.75	0.87	77.03
58-58-416	Comal Tackle Co.	14-Jun	23.8	7.28	549	401	77.23	5.680	346.47	13.63	5.47	18.42
58-50-855	Village of San Leanna	26-Jun	25	7.39	615	428	67.73	5.113	311.86	12.68	-	87.27
58-50-223	City of Sunset Valley	26-Jun	23.7	7.05	602	416	89.52	6.093	371.66	12.06	12.13	10.45
58-49-911	Chaparral Park #2	27-Jun	24.7	6.83	800	568	86.74	5.271	321.55	13.44	2.06	157.46
58-50-847	Creedmoor-Maha #2	27-Jun	23.9	7.11	577	387	72.85	5.077	309.71	10.51	4.89	46.14
58-49-918	Chaparral Park #4	2-Jul	24	6.90	793	486	88.52	5.604	341.87	16.12	2.89	62.12
58-49-915	Chaparral Park #3	2-Jul	23.1	6.84	831	533	88.62	5.419	330.55	25.37	2.24	100.63
58-50-852	J. D. Malone	3-Jul	24.3	7.29	643	414	56.96	4.200	256.21	19.73	1.19	84.37
58-58-413	City of Buda #3	5-Jul	26	7.30	677	439	59.35	4.388	267.64	9.57	-	116.99
58-58-106	City of Buda #2	5-Jul	23.5	7.24	573	380	68.67	4.995	304.69	10.35	3.86	39.82
58-58-403	City of Buda #1	5-Jul	23	7.12	583	378	72.6	5.079	309.79	10.31	5.68	27.38
58-50-830	Slaughter Cr. Ac. #1	5-Jul	24.4	7.15	614	395	59.32	4.194	255.83	13.36	1.27	82.70
58-50-829	Slaughter Cr. Ac. #2	5-Jul	24.6	7.20	664	421	57.3	4.118	251.21	13.91	-	112.59
58-57-901	Hays High School	9-Jul	23.7	7.40	506	347	64.63	4.889	298.21	8.35	3.48	16.07
58-57-804	Michaelis Ranch	9-Jul	24.9	7.22	617	420	70.96	5.131	313.00	12.01	7.60	51.42
58-50-731	Shady Hollow Estates	9-Jul	22.8	7.08	550	375	72.66	5.006	305.37	11.89	3.85	17.42
58-58-219	Pool & Rogers Co.	10-Jul	24.8	7.32	803	554	56.67	4.210	256.83	41.67	-	154.95
58-58-202	Mystic Oaks WSC #1	11-Jul	24.6	7.27	792	629	61.91	4.541	277.00	-	-	218.85
58-58-216	Mystic Oaks WSC #2	11-Jul	24.2	7.09	1047	611	60.04	4.153	253.32	-	-	229.58
58-50-724	Manchaca Fire Dept.	11-Jul	22.7	7.14	527	349	62.68	4.416	269.38	9.62	3.46	31.27
58-57-910	Mt. City Oaks WSC	12-Jul	21.8	6.86	558	345	68.43	4.235	258.32	9.68	4.94	16.72
58-57-9M	Leo Miller	12-Jul	23.4	7.05	570	371	73.97	5.034	307.10	11.43	5.53	16.16
58-57-205	Don West Ranch	14-Jul	25.5	6.80	665	424	91.6	5.461	333.14	11.72	4.57	32.21
58-57-204	Don West Ranch	14-Jul	25.9	6.81	718	456	96.1	5.767	351.78	10.96	19.51	15.27

Table 3: Chemical analysis from water samples in the study area

Well Number	Owner	Date 1990	Temp. (°C)	pH	Cond. (µS)	TDS (mg/l)	DIC (ppm C)	Alkalinity (meq/l)	HCO3 (mg/l)	Cl (mg/l)	NO3 (mg/l)	SO4 (mg/l)
			Field Data				Carbon Species			Anions		
58-57-202	Don West Ranch	14-Jul	25.6	6.96	537	331	67.99	4.442	270.94	9.79	0.54	18.87
58-57-607	Buda/Kyle Church	16-Jul	23.9	7.15	651	391	72.39	5.118	312.20	13.20	6.20	18.57
58-42-821	Trigg Building	16-Jul	22.3	7.22	528	362	57.64	4.168	254.25	22.50	2.38	35.34
58-50-733	Suburban Austin WSC	17-Jul	24.4	7.01	549	360	69.21	4.629	282.39	11.53	5.85	19.33
58-49-922	Copper Hills #2	17-Jul	25.6	7.04	515	345	73.57	4.986	304.15	3.40	0.73	10.80
58-50-838	Village of San Leanna	17-Jul	25.6	7.10	611	367	59.55	4.135	252.22	-	1.86	74.65
58-58-208	Suburban Austin WSC	17-Jul	24.4	7.15	676	427	57.9	4.094	249.71	9.93	-	115.51
58-50-729	VFW Post #3377	18-Jul	24.1	7.21	548	350	61.62	4.442	270.98	11.54	7.04	34.03
58-58-510	Crestview R.V. Center	18-Jul	25.9	7.29	720	451	55.26	4.075	248.56	31.25	0.11	109.08
58-58-218	AAA Petroleum Dist.	18-Jul	25.9	7.01	829	523	75.56	5.054	308.30	36.19	-	110.96
58-50-520	Mr. Herb Mendieta	18-Jul	24.4	7.08	559	358	71.27	4.910	299.52	11.34	6.68	16.85
58-42-913	Park Hill Baptist Ch.	19-Jul	23.7	7.11	643	436	80.42	5.605	341.89	19.33	8.56	23.66
58-49-9B	SW Territories #5	23-Jul	25.7	7.08	695	466	76.42	5.265	321.17	7.59	1.09	89.25
58-50-704	Marbridge Found. #5	24-Jul	24.3	7.12	538	358	68.64	4.801	292.89	10.68	3.48	21.04
58-50-703	Marbridge Found. #2	24-Jul	25.1	7.08	536	362	71.05	4.895	298.60	11.22	5.45	19.87
58-50-854	St. Albans Epis. Ch.	30-Jul	26.5	7.06	3160	1991	56.68	3.874	236.30	545.20	-	598.70
58-58-2E	Hunter Industries	30-Jul	27.6	7.00	759	459	54.51	3.630	221.40	24.15	-	139.97
58-50-7E	Mr. Richard McKeane	31-Jul	23.6	7.06	619	406	75.12	5.134	313.17	19.62	4.22	22.71
58-50-859	Onion Creek Mem.	31-Jul	25.3	7.27	628	388	58.45	4.287	261.52	10.17	-	81.35
58-50-519	Mr. Don West	31-Jul	26.5	7.07	759	475	55.36	3.799	231.73	31.85	0.41	129.57
58-50-835	Onion Creek CC	2-Aug	26.5	7.20	642	384	59.06	4.245	258.92	15.00	3.62	74.66
58-50-843	Oak Forest Highlands	2-Aug	25.7	7.03	643	384	57.43	3.876	236.41	11.11	2.53	97.81
58-50-4R	Mr. Tom Roudebush	2-Aug	25.3	7.09	597	391	74.41	5.147	313.95	24.70	9.01	10.47
58-50-726	Ms. Jane Pratt	6-Aug	25.9	7.28	540	358	65.6	4.825	294.30	12.38	6.48	18.71
58-50-858	Twin Creeks WSC	6-Aug	25.9	7.07	567	351	60.45	4.148	253.04	12.01	7.58	45.53
58-50-8M	Mooreland Water Co.	7-Aug	25.3	6.98	574	370	69.65	4.594	280.26	17.26	4.67	34.27
58-58-1H	Hays Hills Baptist Ch.	7-Aug	25.1	7.25	539	384	66.88	4.879	297.59	11.84	3.49	17.72
Barton Springs	City of Austin	9-Aug	21.1	6.60	690	393	69.33	3.546	216.28	45.72	8.37	39.90

Table 3 (cont.): Chemical analysis from water samples in the study area

Well Number	Owner	Al (mg/l)	Ba (mg/l)	Ca (mg/l)	Cr (mg/l)	Fe (mg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	Pb (mg/l)	Sr (mg/l)	Zn (mg/l)	Charge Balance (%)
		Cations											
58-58-1A	Frank Burdette	0.041	0.045	79.76	0.010	-	0.556	23.55	5.986	0.148	0.205	0.003	12.31
58-58-115	Estate Utilities WSC	0.040	0.041	70.28	0.012	-	0.429	28.76	5.269	0.127	0.265	0.005	11.87
58-58-508	Goforth WSC	0.056	0.090	61.38	0.018	0.028	1.685	35.53	8.545	0.187	-	0.418	1.67
58-58-412	Plum Creek WSC	0.045	0.209	71.14	0.014	-	1.238	30.82	6.707	0.187	-	0.434	2.41
58-58-102	Cimarron Park WSC	0.028	0.065	61.08	0.008	-	1.133	23.86	6.220	0.124	5.438	-	10.52
58-58-114	Cimarron Park WSC	0.029	0.038	68.71	0.010	-	1.034	25.66	6.167	0.128	0.739	0.004	9.63
58-58-117	Twin Oaks Ranch	0.043	0.043	57.49	0.013	-	1.571	29.11	5.656	0.132	6.816	0.114	12.15
58-58-407	Texas-Lehigh Cement	0.048	0.198	71.19	0.014	-	1.240	31.10	6.638	0.190	-	0.401	3.30
58-58-416	Comal Tackle Co.	0.038	0.044	87.08	0.007	-	1.262	20.36	7.393	0.164	0.272	0.010	13.02
58-50-855	Village of San Leanna	0.050	0.092	63.52	0.013	-	1.886	29.79	9.946	0.173	-	0.399	2.35
58-50-223	City of Sunset Valley	0.050	0.345	74.86	0.014	-	1.413	30.35	9.229	0.161	0.964	0.013	13.49
58-49-911	Chaparral Park #2	0.077	0.151	100.20	0.029	-	5.398	51.62	8.154	0.212	8.409	0.016	14.28
58-50-847	Creedmoor-Maha #2	0.046	0.131	69.66	0.012	-	1.547	26.41	6.952	0.159	-	0.357	9.43
58-49-918	Chaparral Park #4	0.080	0.057	107.80	0.023	-	2.381	42.98	7.452	0.203	2.324	0.014	23.51
58-49-915	Chaparral Park #3	0.081	0.100	106.90	0.023	-	4.294	43.40	14.470	0.233	-	0.387	17.93
58-50-852	J. D. Malone	0.069	0.074	65.37	0.017	-	3.768	33.60	22.480	0.179	-	0.381	14.27
58-58-413	City of Buda #3	0.083	0.094	74.86	0.020	0.229	2.202	37.35	6.569	0.218	-	0.413	10.24
58-58-106	City of Buda #2	0.044	0.239	71.51	0.011	0.045	1.084	28.82	6.479	0.157	-	0.304	13.67
58-58-403	City of Buda #1	0.045	0.169	79.37	0.011	0.042	1.030	26.89	6.306	0.157	-	0.023	17.18
58-50-830	Slaughter Cr. Ac. #1	0.064	0.084	69.21	0.016	0.043	1.765	32.34	11.070	0.172	-	0.387	13.05
58-50-829	Slaughter Cr. Ac. #2	0.064	0.091	68.79	0.017	0.089	1.724	33.69	10.760	0.182	-	0.403	8.46
58-57-901	Hays High School	0.055	0.059	68.98	0.011	0.046	1.022	30.02	5.488	0.146	2.586	0.020	20.52
58-57-804	Michaelis Ranch	0.071	0.140	75.77	0.019	0.049	2.442	39.93	7.325	0.176	-	0.262	17.86
58-50-731	Shady Hollow Estates	0.054	0.053	91.40	0.009	0.043	0.868	24.48	6.662	0.172	0.460	0.047	22.86
58-58-219	Pool & Rogers Co.	0.073	0.055	61.22	0.018	0.423	6.545	36.91	68.410	0.176	-	0.335	11.13
58-58-202	Mystic Oaks WSC #1	0.087	0.050	79.79	0.024	0.073	8.935	46.17	77.730	0.208	-	0.340	18.76
58-58-216	Mystic Oaks WSC #2	0.063	0.038	70.56	0.024	0.135	9.550	48.70	71.900	0.181	-	0.346	16.97
58-50-724	Manchaca Fire Dept.	0.071	0.134	75.15	0.012	0.047	2.130	28.04	6.421	0.172	-	0.259	21.53
58-57-910	Mt. City Oaks WSC	0.039	0.049	92.21	0.002	0.051	0.774	18.07	5.699	0.168	0.198	0.001	26.17
58-57-9M	Leo Miller	0.047	0.049	84.93	0.009	0.052	0.965	26.35	6.646	0.157	0.362	0.123	21.59
58-57-205	Don West Ranch	0.070	0.086	90.53	0.019	0.055	2.344	38.53	6.094	0.199	-	0.221	23.44
58-57-204	Don West Ranch	0.059	0.080	123.00	0.010	0.054	0.326	28.86	6.394	0.210	1.449	0.006	27.19

Table 3 (cont.): Chemical analysis from water samples in the study area

Well Number	Owner	Al (mg/l)	Ba (mg/l)	Ca (mg/l)	Cr (mg/l)	Fe (mg/l)	K (mg/l)	Mg (mg/l)	Na (mg/l)	Pb (mg/l)	Sr (mg/l)	Zn (mg/l)	Charge Balance (%)
		Cations											
58-57-202	Don West Ranch	0.052	0.120	66.23	0.012	0.054	3.783	32.79	5.353	0.151	7.338	0.021	25.66
58-57-607	Buda/Kyle Church	0.056	0.052	99.06	0.007	0.070	1.257	21.95	7.550	0.178	0.244	0.019	22.43
58-42-821	Trigg Building	0.049	0.055	83.97	0.007	0.053	0.972	22.74	12.390	0.154	0.441	0.121	20.46
58-50-733	Suburban Austin WSC	0.050	0.055	89.42	0.009	0.048	0.857	24.13	6.885	0.165	1.213	0.011	24.47
58-49-922	Copper Hills #2	0.061	0.084	75.43	0.014	0.046	1.471	33.77	2.499	0.161	1.704	0.018	26.74
58-50-838	Village of San Leanna	0.066	0.148	71.82	0.011	0.053	1.482	29.94	7.338	0.194	-	0.397	17.14
58-58-208	Suburban Austin WSC	0.077	0.095	75.14	0.017	0.070	1.909	38.20	7.521	0.214	-	0.397	12.97
58-50-729	VFW Post #3377	0.050	0.151	69.14	0.006	-	1.321	25.74	7.236	0.154	-	0.278	15.63
58-58-510	Crestview R.V. Center	0.052	0.033	57.09	0.012	-	4.739	34.40	37.050	0.146	-	0.349	10.03
58-58-218	AAA Petroleum Dist.	0.052	0.056	71.72	0.016	-	4.110	37.68	42.030	0.167	-	0.324	10.78
58-50-520	Mr. Herb Mendieta	0.033	0.146	77.26	0.007	-	0.565	25.25	6.500	0.126	2.751	-	19.00
58-42-913	Park Hill Baptist Ch.	0.047	0.086	111.60	0.004	-	0.767	19.99	8.175	0.171	0.182	0.013	18.93
58-49-9B	SW Territories #5	0.073	0.116	85.64	0.018	-	3.740	43.42	5.631	0.181	8.085	0.108	17.77
58-50-704	Marbridge Found. #5	0.046	0.053	86.07	0.002	-	0.982	20.37	6.279	0.153	0.333	0.038	19.57
58-50-703	Marbridge Found. #2	0.046	0.047	79.17	0.006	-	0.783	26.10	5.960	0.149	0.308	0.064	19.38
58-50-854	St. Albans Epis. Ch.	0.288	0.052	168.04	0.020	-	18.320	90.16	402.000	0.428	22.516	0.016	5.83
58-58-2E	Hunter Industries	0.073	0.061	70.17	0.016	0.515	2.811	38.42	24.360	0.178	-	0.351	11.71
58-50-7E	Mr. Richard McKeane	0.049	0.084	104.60	0.004	-	1.166	18.77	11.190	0.172	1.836	0.002	21.23
58-50-859	Onion Creek Mem.	0.065	0.136	71.99	0.011	-	1.544	28.79	7.578	0.199	-	0.821	11.37
58-50-519	Mr. Don West	0.068	0.038	55.55	0.013	-	6.243	34.58	51.460	0.173	-	0.342	11.90
58-50-835	Onion Creek CC	0.047	0.134	66.83	0.006	-	1.033	28.22	10.080	0.175	-	0.332	9.46
58-50-843	Oak Forest Highlands	0.050	0.096	64.49	0.009	-	1.057	30.33	8.013	0.175	-	0.324	8.31
58-50-4R	Mr. Tom Roudebush	0.043	0.064	80.98	0.010	-	0.309	31.89	9.419	0.143	0.296	0.005	19.93
58-50-726	Ms. Jane Pratt	0.040	0.054	77.38	0.006	-	0.784	25.30	6.888	0.145	2.490	0.005	19.17
58-50-858	Twin Creeks WSC	0.043	0.142	70.86	0.006	-	0.930	26.36	7.300	0.152	-	0.284	16.11
58-50-8M	Mooreland Water Co.	0.030	0.081	81.52	0.004	-	0.668	23.37	8.390	0.137	6.790	0.031	17.80
58-58-1H	Hays Hills Baptist Ch.	0.161	0.055	100.30	0.006	3.218	0.534	27.61	6.631	0.175	0.259	0.005	29.38
Barton Springs	City of Austin	0.044	0.077	92.64	0.005	-	0.998	24.51	26.320	0.156	2.394	0.001	24.34

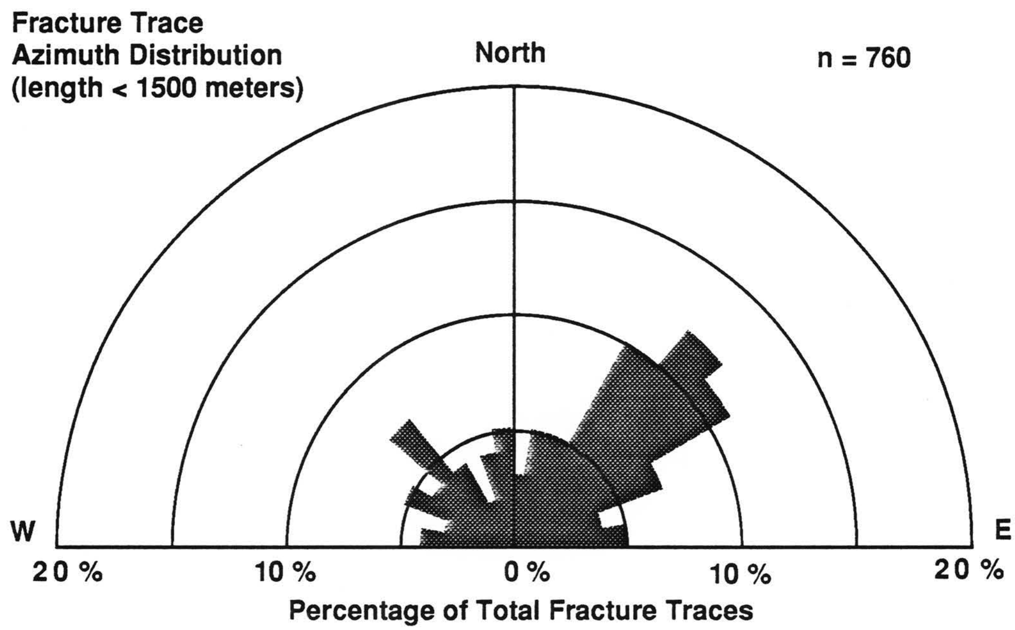
Table 3 (cont.): Chemical analysis from water samples in the study area

V. Results and Discussion

A) Orientations of Lineaments

Analyses of lineaments may be readily expressed by statistical methods. The recognition of patterns in a mass of data not visible by individual measurements and the reduction of a large number of features to a small number of significant numbers is a goal of statistics. Hence, a major emphasis of lineaments and fracture traces lies in the population of features. In this way, statistical conclusions are more important than the exact location, length, or orientation of any single lineament.

Lineaments and fracture-trace azimuths in this study were separated and displayed as Rose diagrams to illustrate any regional trend in the orientation of linear features (Figure 8). Gay (1976) recommends utilizing a smooth-curve Cartesian histogram to quantitatively display the results of lineament orientations. One of the principle advantages of this type of plot is the ability to select an unique azimuth to characterize each peak in the plot. This is accomplished by dividing the peak into equal areas on each side of a vertical line. Thus characterized, the grouping of linear features can then be quantitatively compared with



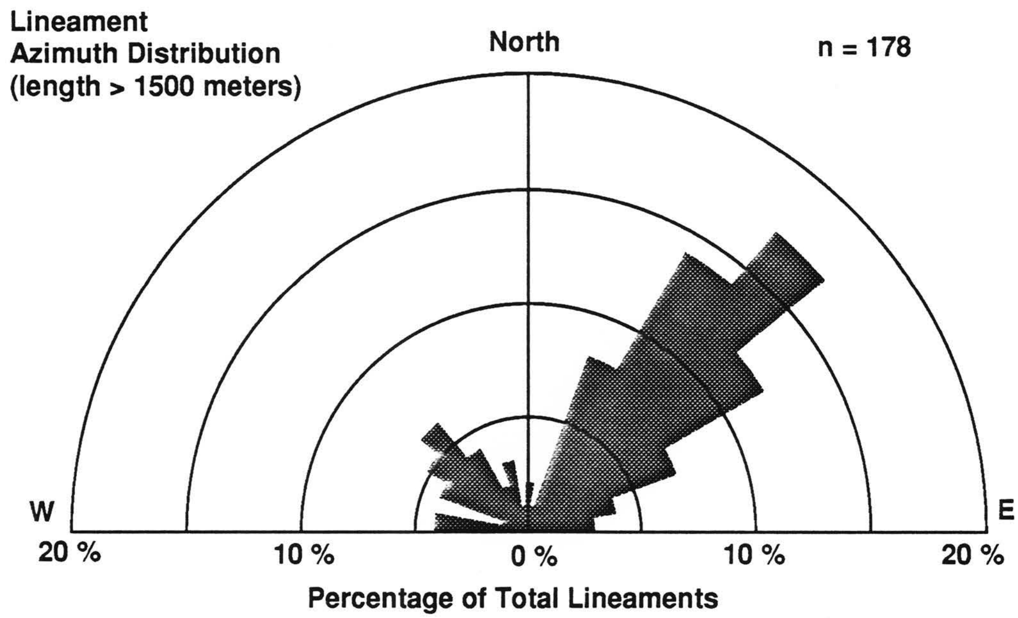
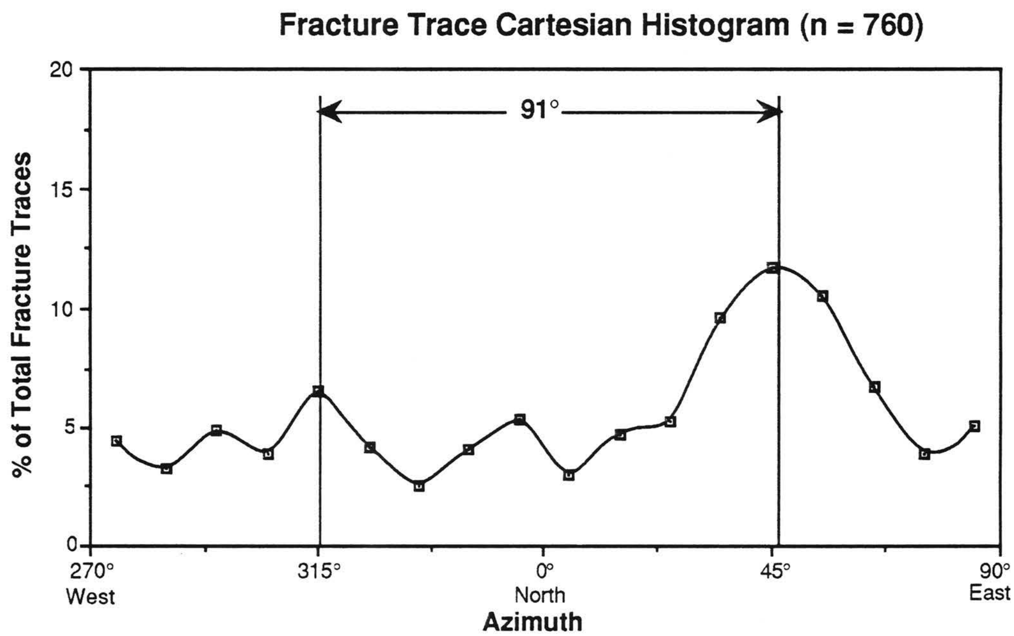


Figure 8: Rose diagrams of lineament and fracture trace orientations in the study area



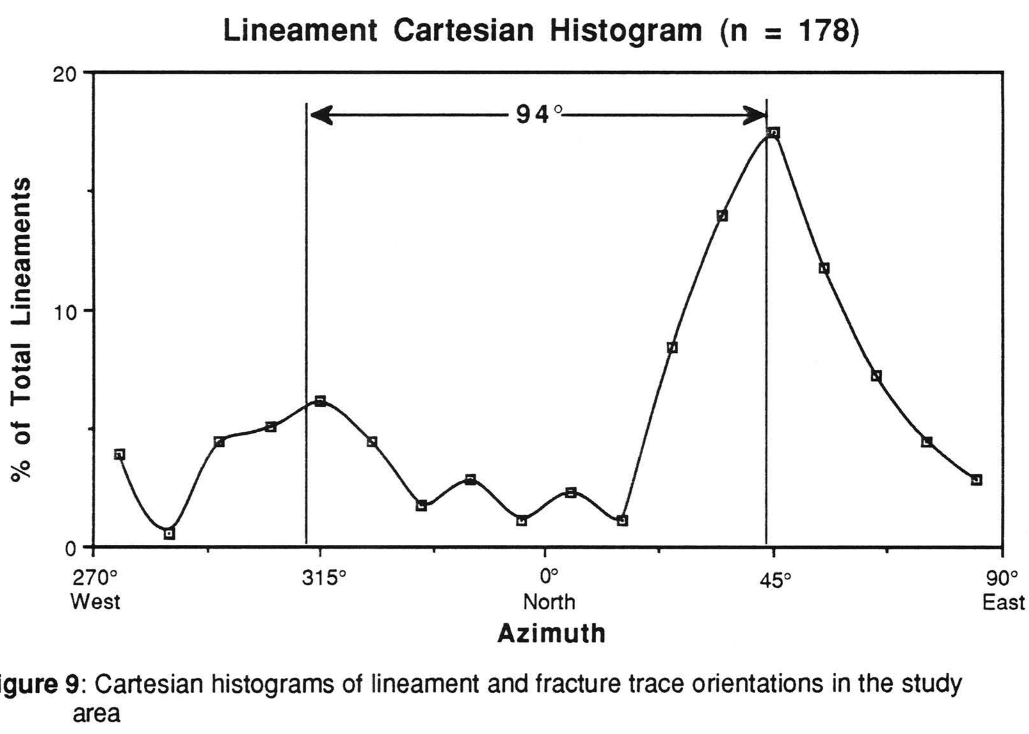


Figure 9: Cartesian histograms of lineament and fracture trace orientations in the study area

other sets. Furthermore, the dispersion of orientations in a set is readily visible as the width of the plotted peak. Additionally, closely spaced peaks, which may each represent distinct sets of linear features, are easily separated and distinguished on histogram plots as well as the low or poorly developed peaks. A smooth-curve Cartesian histogram of the fracture traces and lineaments in the study area is illustrated in Figure 9.

Both types of diagrams clearly show the bimodal orientation of the azimuth data. A rectangular graph of relative length versus azimuth is depicted in Figure 10 and reveals the two peaks which exceed the average relative length. The largest peak ranges in azimuth from 20°

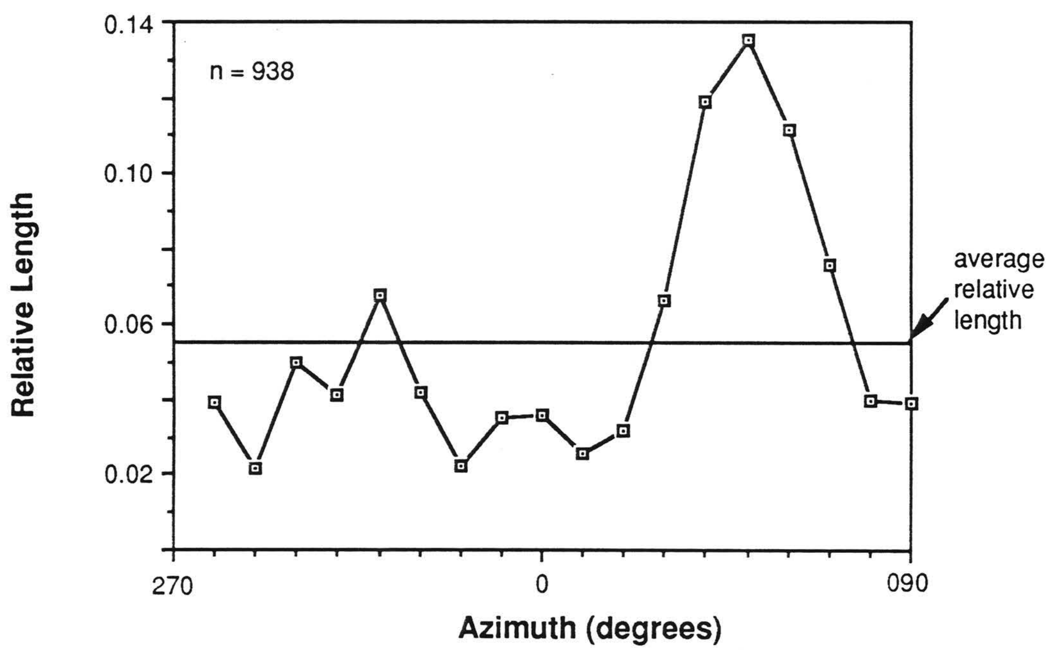


Figure 10: Rectangular graph showing relation between values of lineament azimuth and relative lineament length in the study area.

- 70°. A secondary peak is confined to the sector 130° - 140°. These results unequivocally concur with the findings of Woodruff, *et al.* (1989). The significance of each peak is determined by a statistical analysis (Table 4). Tabulated data for each 10° sector includes: total lineament length ($\mathbf{L_s}$); average lineament length ($\mathbf{L_a}$); number of lineaments (**n**); relative length ($\mathbf{L_r}$); length-weighted frequency (**F**); and index of preferred orientation (**IPO**). For the two major peaks, the chi square values (χ^2) and the Bernshtein accuracy criterion (H) are listed. The substantial chi square value for the largest peak (72.168) confirms the overall trend in the azimuth data.

Figure 11 shows that mean length of lineaments in each 10° sector tends to increase with lineament frequency and sector length. This phenomenon has been previously reported (Haman & Jurgens, 1976; Reeves, 1976) and indicates that lineament peaks are defined both by high frequencies and by lineaments of greater mean length. However, in the Edwards aquifer, the similarity between the curves for frequency and sector length suggests that the size of a peak (sector length) is more a function of the number of lineaments forming it than of the size of these lineaments.

From Table 4, the index of preferred orientation is the sum of the **IPO** values calculated for each sector. The resulting value for **IPO** (25.8%) is over twice as high as in Dix and Jackson's (1981) report for equivalent numbers of random model lineaments. This suggests that the peakedness of data in this study is not random but results from

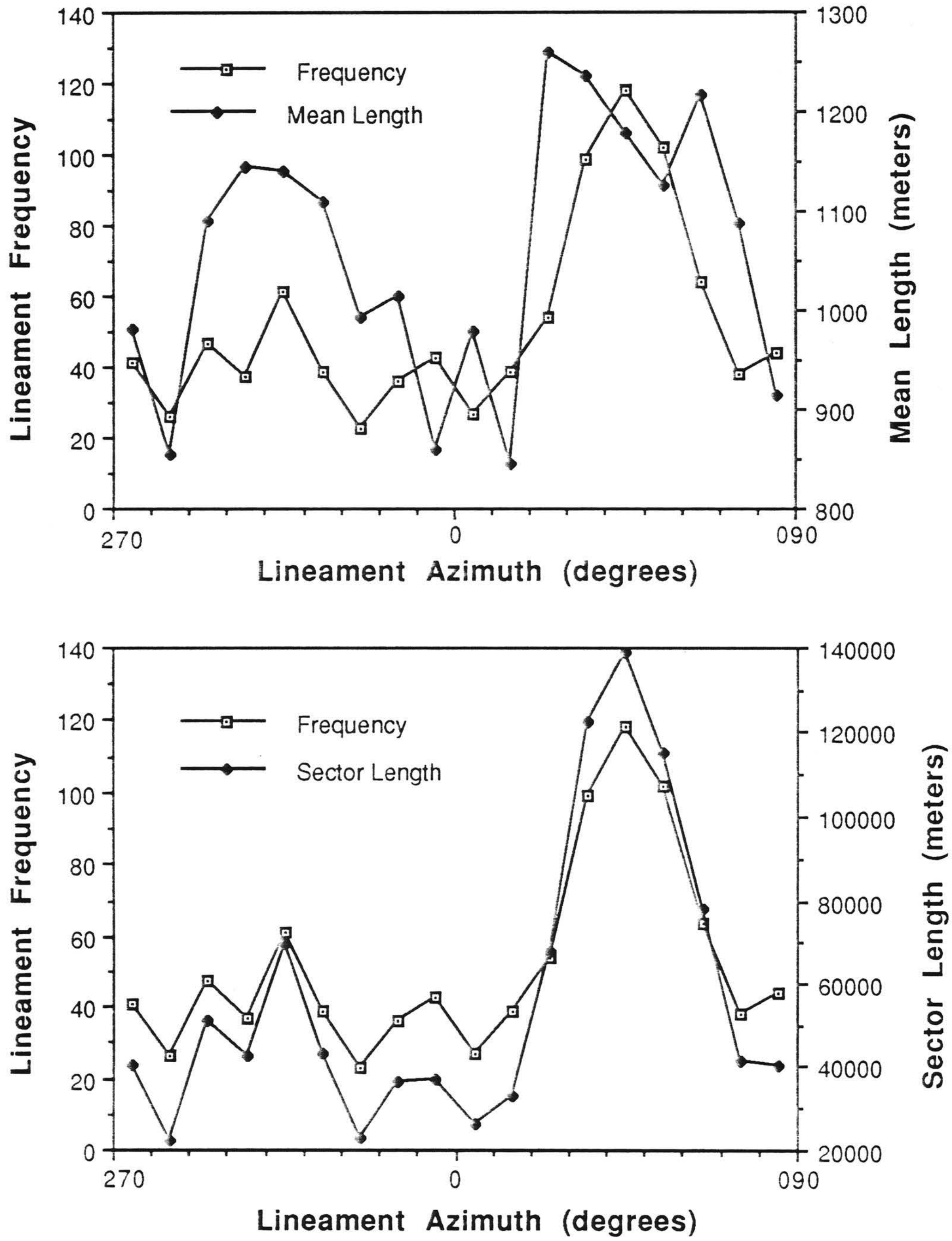


Figure 11: Values for mean length (top figure), sector length (bottom), and frequency of lineaments in the study area

directional control of lineaments, which produces IPO values as much as twice as high as those generated randomly.

The statistical analysis confirms the trend illustrated in the Rose diagrams and cartesian histograms: the statistically significant majority of lineaments and fracture traces in the study area lay in a northeastern-southwestern direction. This result is expected due to the presence of the associated faults, fractures, and joints of the Balcones fault zone. The secondary peak exists approximately 90° from the primary peak corresponding to the prevailing joint directions associated with the fault zone as described by Dunaway (1962). Myrick *et al.* (1988), in a study on the Northern Balcones Edwards aquifer, confirmed that lineaments are related to regional structural trends but orientation becomes increasingly random away from faulting. Thus, lineaments and fracture traces in the study area reflect the tectonic stresses resulting from the Balcones-Ouachita structural belt and correlate well with the primary fault trend of N 40 E and the corresponding joint trend of N 45 W.

B) Correlation between Well Proximity and Locations of Lineaments

The distances between each of the 27 wells with specific-capacity data and the nearest fracture trace or lineament to each well was determined using the U. S. Geological Survey's ARC/Info Geographic Information System. Due to the large ranges between values for specific capacity and distance, the data was plotted on a log-log scale. A majority

Table 4: Summary of selected statistical analysis of lineament azimuths

RANGE IN AZIMUTH (in degrees)

	0-10	10- 20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
Sector Length (Ls)	26407	32999	67964	122328	139046	114938	77802	41338	40189
No. of Lineaments (n)	27	39	54	99	118	102	64	38	44
Mean Length (La)	978.0	846.1	1258.6	1235.6	1178.4	1126.8	1215.7	1087.9	913.4
Relative Length (Lr)	0.026	0.032	0.066	0.119	0.135	0.112	0.076	0.040	0.039
Length-Weighted Frequency (F)	0.694	1.252	3.570	11.780	15.960	11.404	4.844	1.528	1.720
Index of Preferred Orientation (IPO)	0.030	0.023	0.011	0.063	0.080	0.056	0.020	0.015	0.016
Chi Square (sector)			0.011	17.009	39.395	15.449	0.305		
Chi Square				X2 =	72.168				
Bernshtein criterion				H =	18.042				

note: all lengths are in meters

Table 4 (continued): Summary of statistical analysis of lineament azimuths

RANGE IN AZIMUTH (in degrees)

	90-100	100-110	110-120	120-130	130-140	140-150	150-160	160-170	170-180
Sector Length (Ls)	40209	22201	51225	42366	69497	43281	22842	36476	36927
No. of Lineaments (n)	41	26	47	37	61	39	23	36	43
Mean Length (La)	980.7	853.9	1089.9	1145.0	1139.3	1109.8	993.1	1013.2	858.8
Relative Length (Lr)	0.039	0.022	0.050	0.041	0.068	0.042	0.022	0.035	0.036
Length-Weighted Frequency (F)	1.604	0.561	2.342	1.525	4.124	1.642	0.511	1.277	1.545
Index of Preferred Orientation (IPO)	0.016	0.034	0.006	0.014	0.012	0.013	0.033	0.020	0.020
Chi Square (sector)					0.033				
Chi Square				X2 =	0.033				
Bernshtein criterion				H =	0.000				

note: all lengths are in meters

of the wells with large specific-capacity values are located to the southeast of a northeast-southwest trending lineament. These wells were separately plotted and statistically analyzed to confirm if the differences observed were due to chance or some type of controlling hydrogeologic factor.

Plots showing the relation between values of specific capacity and distance based on the classification of the lineament ("1-man", "2-man" or "3-man") are presented in Figure 12. The degree of correlation between these values decreases as the number of interpreters who identified the lineament increases. It seemed intuitive at the beginning of the study to assume that a greater degree of correlation would occur with lineaments that had been identified by all three interpreters because these lineaments are more obvious and, thus, more likely to be true structural features. However, only 48 of the 938 total lineaments in the study area were identified by all three interpreters. Combined with the relatively small number of specific-capacity values, the 48 "3-man" lineaments are too sparsely distributed to show any correlation with the specific-capacity data.

A good correlation exists with increased specific-capacity values and decreased distances to the nearest lineament, regardless of its classification. As shown in Figure 12, this correlation is especially evident for wells located within 200 feet (61 meters) of a lineament. Any mathematical correlation is complicated by the extremely large specific-capacity value of the well located at Mountain City Oaks Water Supply

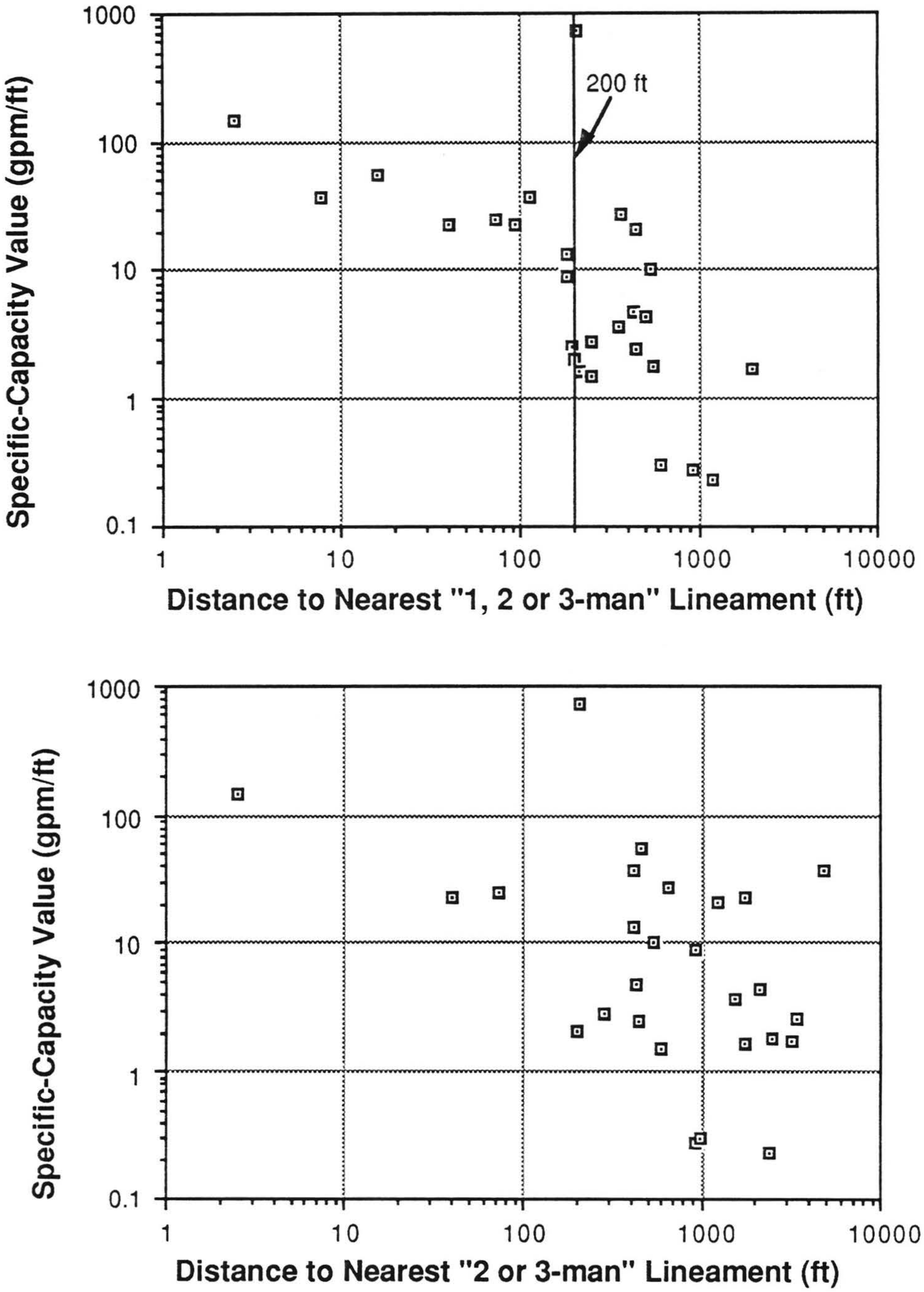
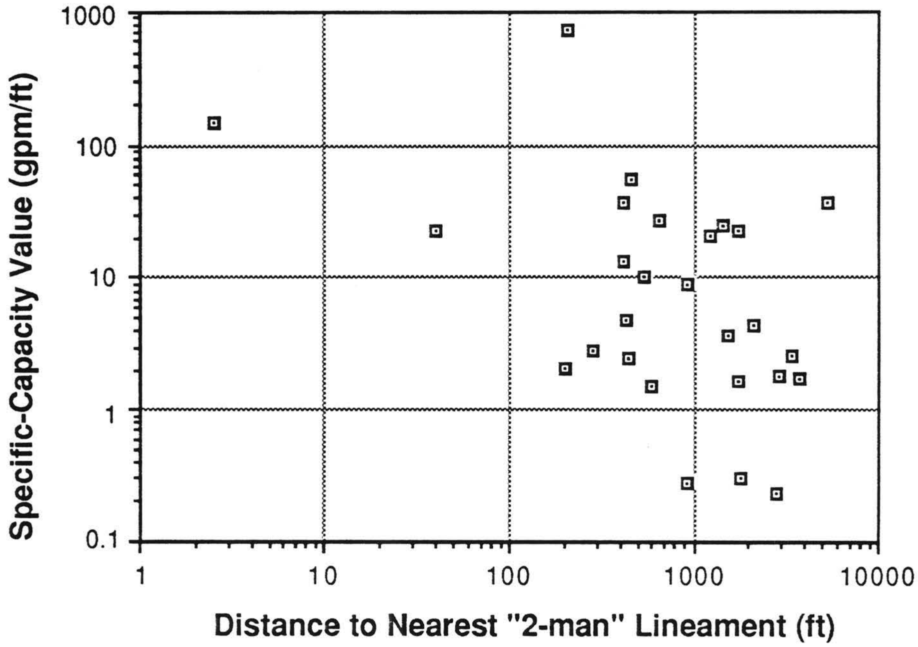


Figure 12: Well productivity and the lineament type in the study area



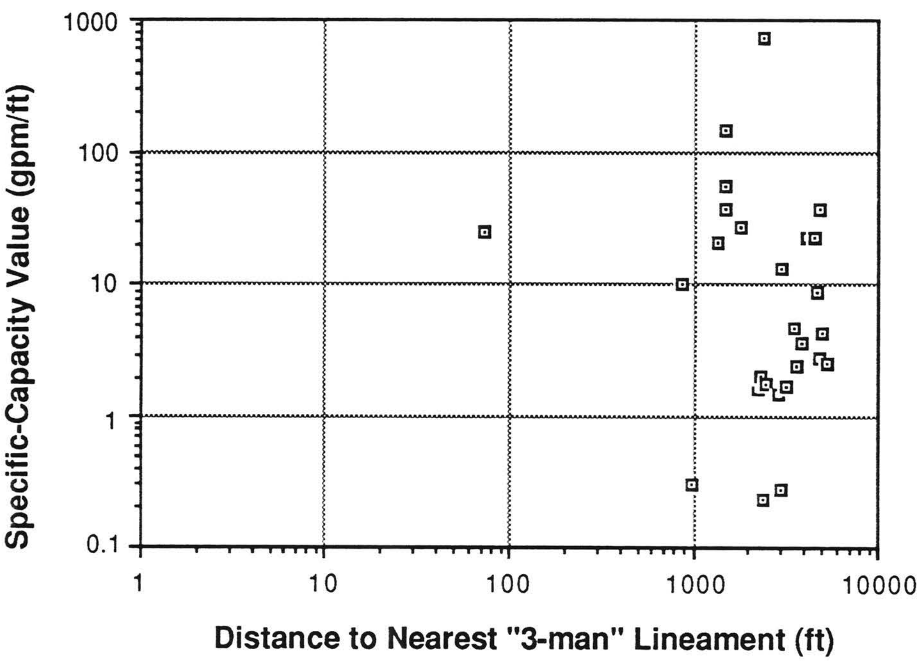


Figure 12 (cont.): Well productivity and the lineament type in the study area

Company. Here, the well was pumped at 184 gallons per minute with a drawdown of only 3 inches (7.6 cm), but is located 207 feet (63 meters) from the nearest lineament. An examination of the drilling log for that well, however, shows that two large "cavernous openings" were encountered during drilling.

Despite the lack of correlation between specific capacity and "3-man" lineaments, it is still recommended that lineament analyses are conducted by more than one interpreter. Typically, lineaments are interpreted from aerial photographs during a limited viewing time. To a point, multiple interpreters are able to identify more lineaments in the same time restrictions. The importance of lineament analysis is in the total distribution of lineaments and fracture traces in any one area.

C) Correlation between Well Productivity and Directions to Lineaments

More important than distance to the nearest lineament is the direction of the well from the lineament and the orientation of that lineament. Table 5 lists the 27 wells in order of increasing specific-capacity values. As shown in the second column from the right, 10 of the 13 most productive wells are located to the southeast of a linear feature. None of the 13 least productive wells were located within 1000 feet (305 meters) to the southeast of a lineament. These "southeast" wells were separated from the rest of the data set and graphed separately. As shown in Figure 13, wells located southeast of a lineament show a

Well Number	Well Name	Spec. Cap. Value (gpm/ft)	Direction (from lineament)	Order of Rank
58-58-202	Mystic Oaks WSC #1	0.23	SW	1
58-50-830	Slaughter Creek Acres	0.28	S	2
58-50-8A	Native Texas Nursery	0.30	SW	3
58-42-821	Trigg-Forister Bldg.	1.54	NW	4
58-42-8M	Allen Keller Co.	1.67	NE	5
58-58-2E	Hunter Industries	1.71	NE	6
58-58-1EE	Neptune-Wilkinson Co.	1.77	N	7
58-49-9H	Charles Ranch	2.08	SW	8
58-58-508	Goforth WSC #4	2.50	NE	9
58-50-223	City of Sunset Valley	2.52	SW	10
58-50-414	Lee V. Johnson	2.83	NW	11
58-57-307	Dahlstrom Middle Sch.	3.71	NW	12
58-58-413	City of Buda #3	4.33	NE	13
58-58-506	Goforth WSC #2	4.77	NE	14
58-58-412	Plum Creek WSC #2	8.94	SE	15
58-58-1H	Hays Hills Baptist Ch.	10.14	NW	16
58-42-812	W. F. Guyton & Assoc.	13.33	SE	17
58-50-731	Shady Hollow Estates	21.00	SE	18
58-50-835	Onion Creek CC	22.50	NW	19
58-58-406	Texas-Lehigh Cement Co.	22.64	E	20
58-42-8S	Espey Huston & Assoc.	25.00	SE	21
58-58-123	Elizabeth Porter	26.67	SE	22
58-58-1A	Frank Burdette	37.07	SE	23
58-50-704	Marbridge Found. #5	37.10	SE	24
58-58-115	Estate Utilities WSC	55.00	SE	25
58-58-102	Cimarron Park #2	150.00	SE	26
58-57-910	Mt. City Oaks WSC	736.00	SE	27

Table 5: Specific-capacity values ranked in ascending order

greater correlation with specific capacity than wells that do not lie to the southeast of a lineament (Figure 14).

Because of the predominance of southwest-northeast trending structural lineaments in the study area, there is an inherent difference

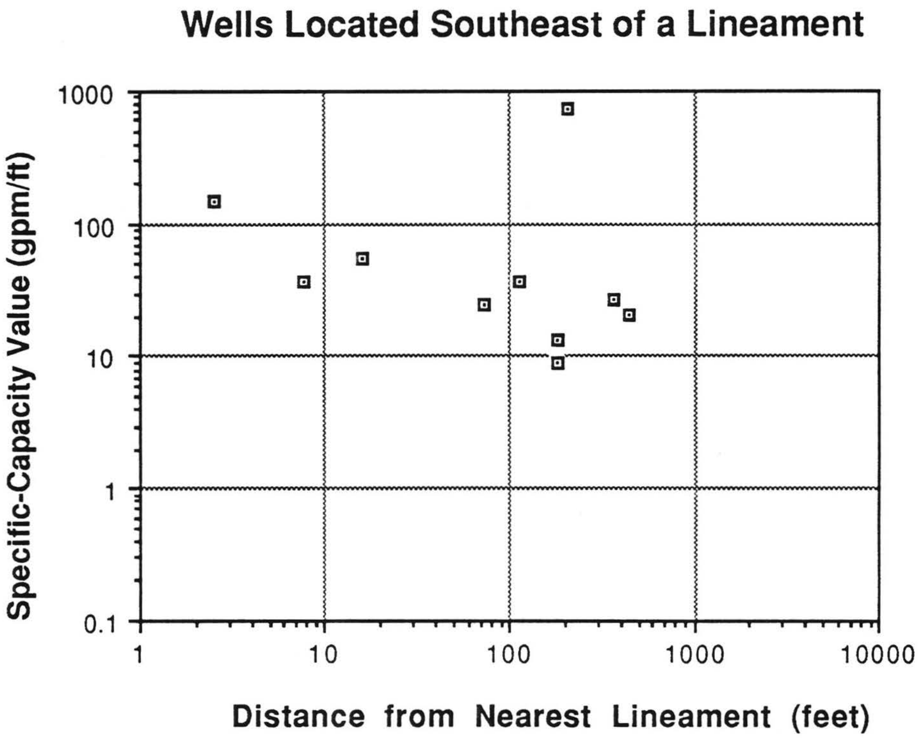


Figure 13: Values of specific capacities and distances from wells to nearest lineament northwest of each SE well

between these types of lineaments as opposed to linear features that do not trend in a SW/NE direction. In order to test this correlation, all non-SW/NE trending lineaments were removed from the data set. Distances from the 27 wells to the nearest SW/NE trending lineament were determined and plotted in Figure 15. In addition, the distance to the nearest SW/NE trending lineament that lies to the northwest of the 27 wells was measured and examined in Figure 16.

Restricting the type of lineaments to only those that trend in a SW/NE direction results in plots that appear to have a better predictive

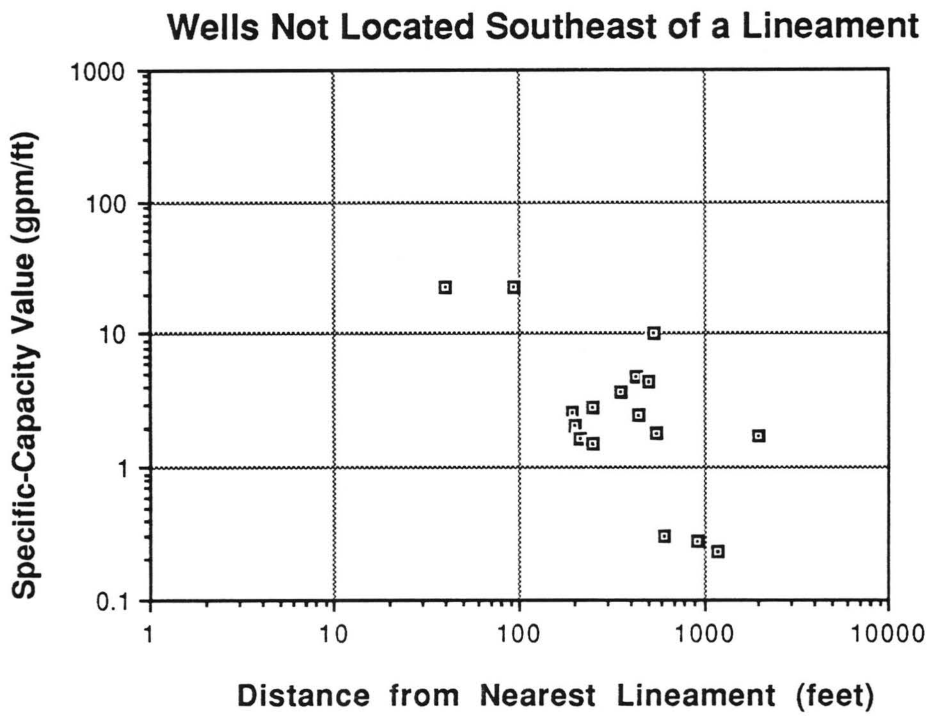


Figure 14: Values of specific capacities and distances from wells to nearest lineament not located northwest of each non-SE well

pattern than the trends illustrated in Figures 13 and 14 when all lineaments were utilized. This is probably due to the predominance of faults and fractures that lie in a southwest/northeast orientation. Because the majority of structural groundwater conduits also run in this direction, a tolerable correlation appears to exist between increased specific-capacity values and decreased distance to the well from a lineament in a southeasterly direction.

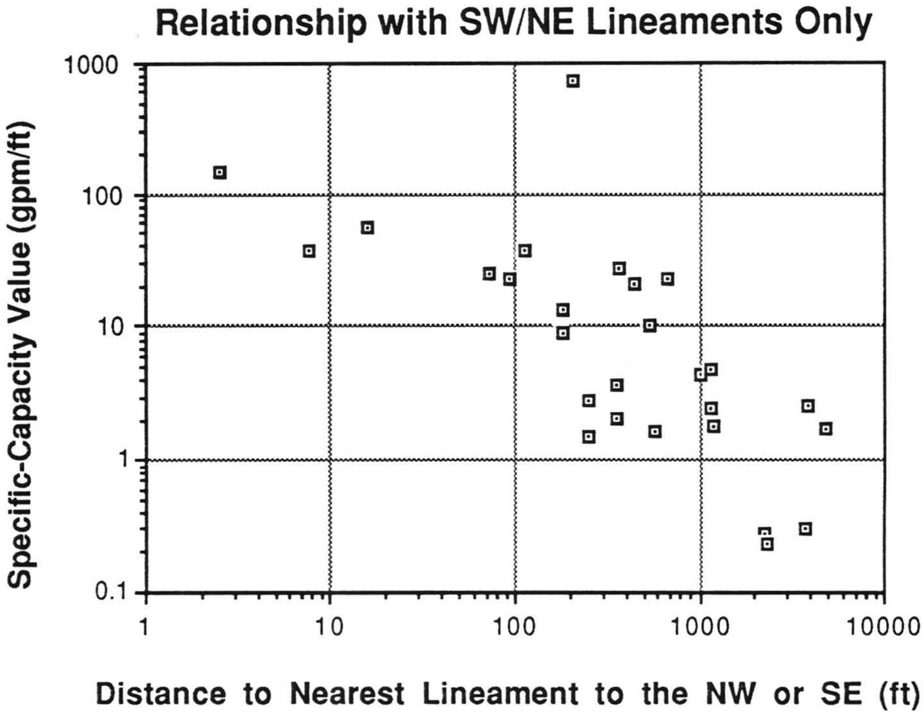


Figure 15: Values of specific capacities and distances to the nearest southwest-northeast trending lineament located to the northwest or southeast of a well

The Mann-Whitney U Test was applied to the specific-capacity data to statistically determine if the difference between specific-capacity values of wells located to the southeast of a SW/NE trending lineament are random data or structurally controlled. The null hypothesis to be tested is: H_0 - direction of a well from a lineament has no effect on specific capacity. The alternative hypothesis is H_1: direction of a well from a lineament has a significant effect on specific capacity. As shown in Table 6, the statistic U is calculated for both southeast wells and non-southeast wells. Since the lower computed U value, 7, is less than the

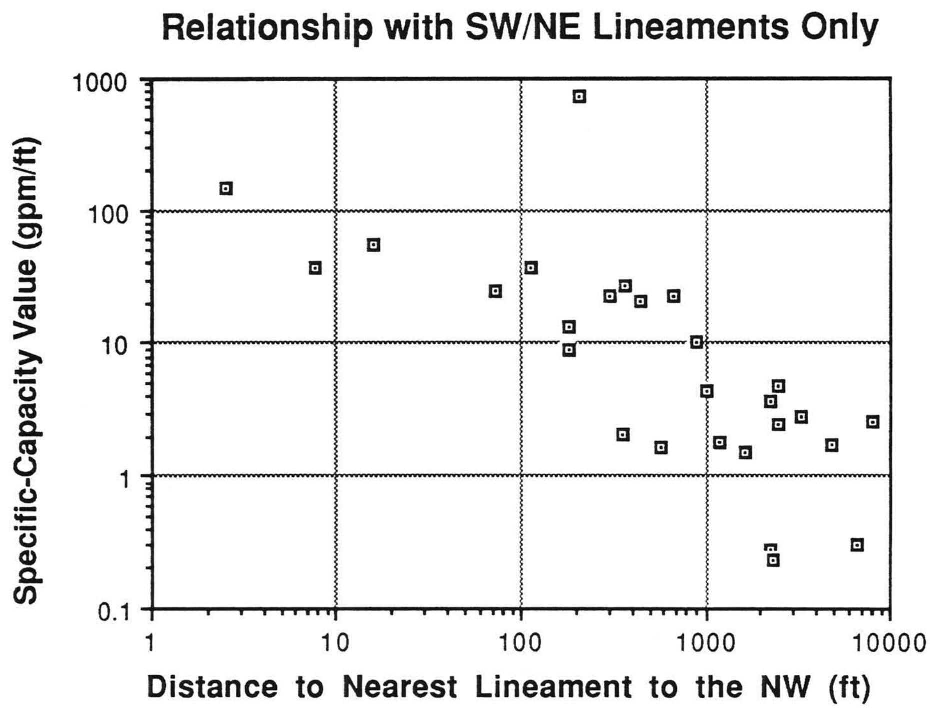


Figure 16: Values of specific capacities and distances to the nearest southwest-northeast trending lineament located to the northwest of the well

expected value of U, 45 (at the 95%-confidence level), the null hypothesis is rejected. As a result, there is a significant difference in well productivity with respect to wells located southeast of SW/NE trending lineaments.

The dominance of large specific-capacity values located southeast of a SW/NE trending lineament is further reinforced upon examining the exceptions in the specific-capacity data. As Table 5 shows, three of the 13 wells with the largest specific-capacity values are not located southeast of a lineament. However, each of these three wells, Texas-

Ranks for Two Groups

SE Wells	*Non-SE Wells*
15	1
17	2
18	3
21	4
22	5
23	6
24	7
25	8
26	9
27	10
	11
	12
	13
	14
	16
	19
	20
$R_1 = 218$	$R_2 = 160$
$n_1 = 10$	$n_2 = 17$
$U_1 = 7$	$U_2 = 163$

Table 6: Summary of Mann-Whitney U test results

Lehigh Cement Co., Onion Creek Country Club, and Hays Hills Baptist Church, have extenuating circumstances which are evident on the base map. The Texas-Lehigh Cement Co. well, while technically just east of a north-south trending lineament, is also equidistant away from the endpoint of a northeast-southwest trending lineament. Likewise, the well at the Onion Creek Country Club is northwest of the nearest lineament but is also only 300 feet (91 meters) to the southeast of a northeast-southwest trending lineament. The Hays Hills Baptist Church location is also located between a series of linear features all of which are oriented in a northeast-southwest direction. Although the well is located northwest of the nearest lineament, it is also located to the southeast of another lineament that, in fact, may have structural control on the well productivity.

Of the 27 wells with specific-capacity values, the 13 largest values are all located to the southeast (within 700 feet or 213 meters) of a northeast-southwest trending lineament or fracture trace. Specific-capacity values for these wells range from 8.94 gpm/ft to 736.0 gpm/ft. Conversely, none of the 14 remaining wells are located within 1000 feet (305 meters) of a southwest-northeast trending lineament or fracture trace. These specific-capacity values range from 0.23 to 4.77 gpm/ft.

Clearly, direction of a well from a lineament is more significant than distance to the nearest lineament. This is to be expected in the Barton-Springs section of the Edwards aquifer because of the attitude of the structural features in the formation. Most faults and fractures are near-vertical and any dip direction is to the southeast. Consequently, the large-yielding wells located to the southeast of northeast-southwest trending lineaments or fracture traces are most likely intersecting highly permeable fracture zones of steeply dipping faults and fractures. Based on Figure 16, a limited range for the specific-capacity values of potential water wells in the study area can be estimated by measuring the distance from the well to the nearest SW/NE trending lineament located to the northwest of the well. For example, a well located 1000 feet (305 meters) to the southeast of a lineament would be expected to have a specific-capacity value of approximately 1 - 10 gpm/ft of drawdown. In this manner, lineament analysis can be used as a tool for predicting reasonable ranges of specific-capacity values for prospective wells.

D) Correlation between Water Chemistry and Locations of Lineaments

Table 3 lists the results of the chemical analysis of 61 water samples collected in the Barton-Springs section of the Edwards aquifer. Chemical parameters were chosen to provide an overall chemical survey of the study area. Specific parameters and ratios were used to evaluate possible chemical relationships between locations of lineaments and large yield water wells. A Piper diagram in Figure 17 displays results similar to those found in other water chemistry surveys of the area (Senger & Kreitler, 1984; Clements, 1989): calcium-bicarbonate waters of the Edwards grading to sodium-sulfate water in the vicinity of the "bad-water" line. Well #58-50-854, located in the "bad-water" zone, is isolated in the sodium-chloride section of the Piper plot.

Bicarbonate values are relatively constant with a mean value of 294 mg/L. At Barton Springs, the discharge point for this section of the aquifer, the bicarbonate value, 216 mg/L, was the smallest value

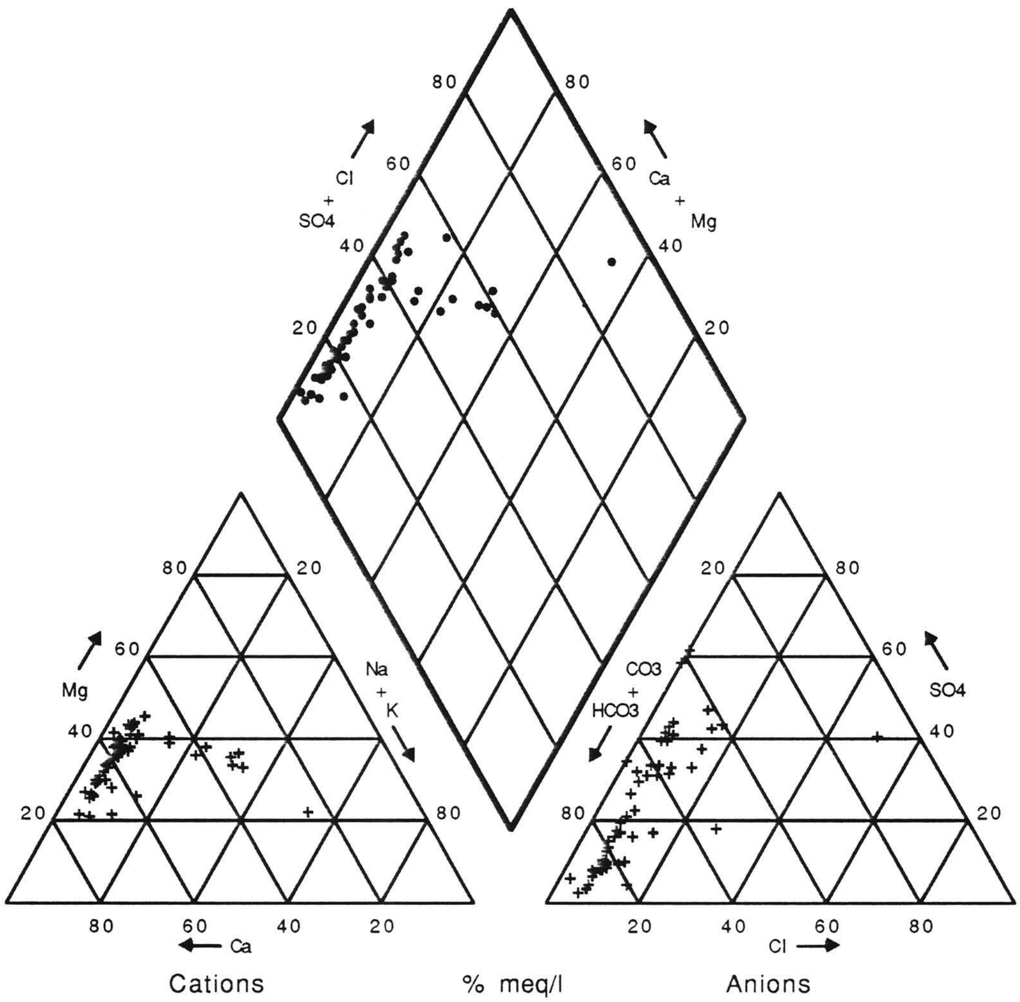


Figure 17: Piper diagram of 61 samples collected from the study area

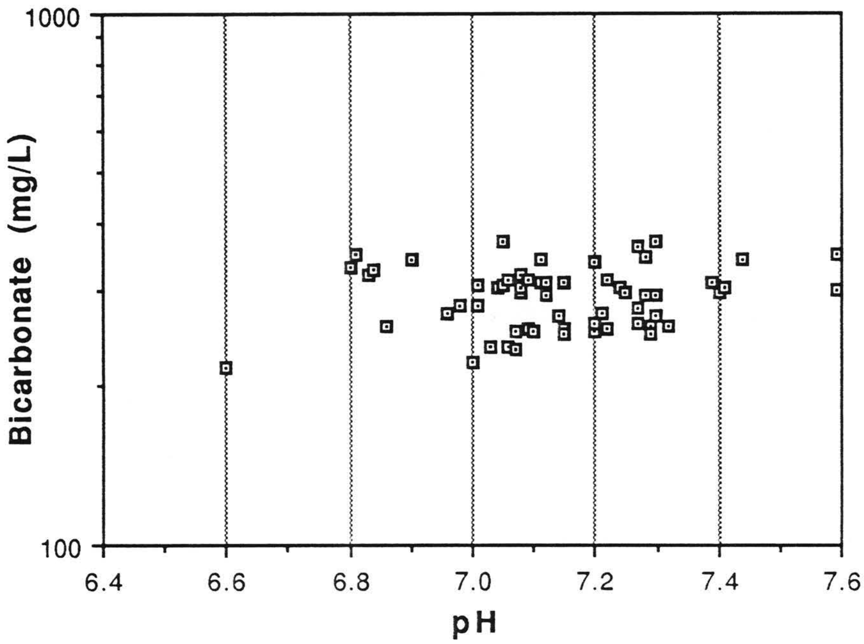
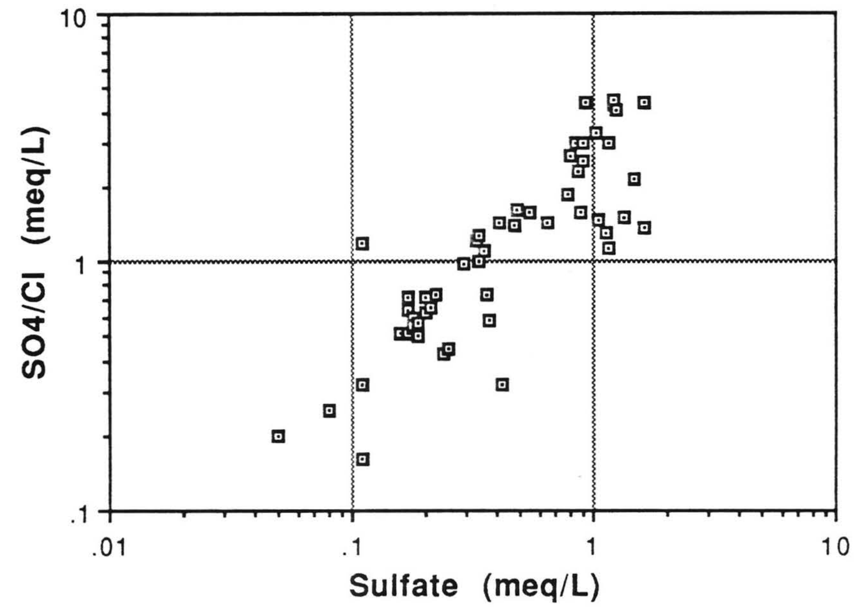


Figure 18: Plot of carbonate chemistry for samples collected in the study area

measured. According to Abbott (1977b), groundwater in the artesian zone of the Edwards aquifer is at least seasonably under-saturated. This undersaturation is partly due to large volumes of groundwater flowing in pipe-like voids where little of the water is actually in contact with the host rock, and partly due to the mixing effect that occurs with the addition of large volumes of undersaturated recharge. Consequently, caverns are probably being enlarged during seasonal conditions with zones of largest permeability receiving the greatest amounts of dissolution. Figure 18 illustrates the relationship between bicarbonate and pH of the collected water samples.

The concentrations of three anions in the collected samples were determined: chloride, nitrate, and sulfate. No flouride, bromide, nitrite, or phosphate was identified in the samples because the concentrations of these parameters were below the method detection level. Chloride concentrations ranged from 3.4 mg/L to 545.2 mg/L. Excluding the well located at St. Alban's Church (#58-50-854), the mean chloride concentration is 15 mg/L throughout the majority of the study area. The St. Alban's Church well has an extremely large chloride concentration which is to be expected with the brine-like water in the "bad-water" zone. Relatively large chloride values appeared along the western, northern, and eastern boundaries. Nitrate concentrations averaged 4.7 mg/L with a maximum value of 19.5 mg/L. This value, however, occurs on the Don West Ranch (#58-57-204) and is likely due to the cattle ranching in the area.

Sulfate and strontium concentrations from the 13 wells with the largest specific-capacity values were also examined. The mean values for sulfate and strontium in the Edwards aquifer from this study are 60.1 mg/L and 2.2 mg/L, respectively. If the fractures near these wells penetrated the underlying Glen Rose Limestone, larger concentrations of sulfate and strontium may have occurred. Sulfate values exist for 9 of the 13 large-flow wells and the mean concentration value is 29.8 mg/L. Similarly, the mean strontium values for the large flow wells are about one-half of the average of all the wells in the study area. In addition, values for both sulfate and strontium vary widely in the large-flow



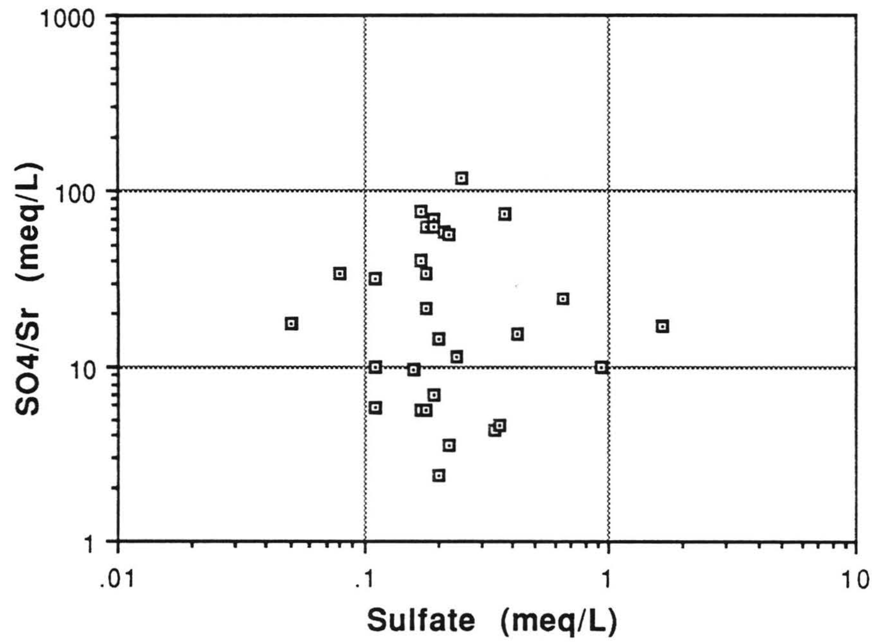


Figure 19: Sulfate ratios versus chloride (top) and strontium (bottom) for samples collected in the study area

wells. Sulfate ratios as compared to chloride and strontium are plotted in Figure 19.

Consequently, no direct correlation can be made with sulfate and strontium concentrations and lineaments. This may be due to a paucity of data, a complex distribution of constituents or a lack of upward

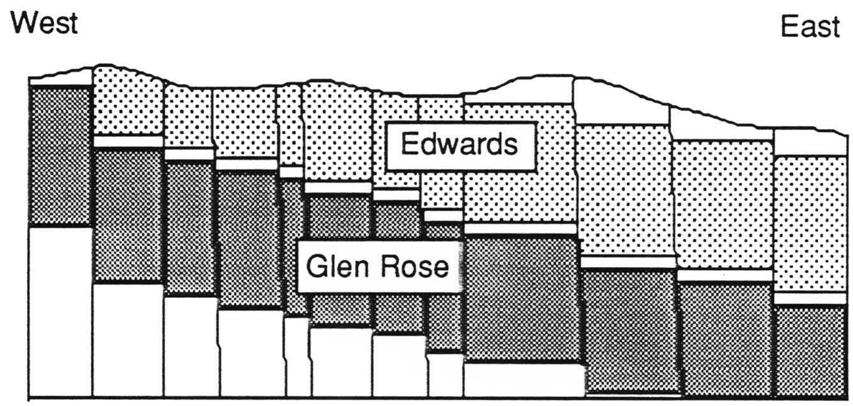


Figure 20: Schematic cross section across the Balcones fault zone (from Senger & Kreitler, 1984)

groundwater movement through vertical fractures from the Glen Rose. The last point is confirmed by Senger & Kreitler (1984): "Leakage from the Glen Rose Limestone is probably not upward through the Walnut Formation into the Edwards Limestone but instead is lateral across fault surfaces" (Figure 20). Similarly, Slade *et al.* (1986) presents an alternative conclusion:

> ....vertical displacements along faults which exceed the thickness of the Walnut Formation would cause the upper Trinity and Edwards aquifers to be in direct contact along

> these faults. Water movement could then occur directly between these two aquifers.

In both cases, lineaments, which indicate vertical faults and fractures, would not be locations of large sulfate and strontium concentrations.

The four major cations, calcium, potassium, magnesium, and sodium all reflect substantial variability among the 61 water samples. Neither calcium or magnesium concentrations display a predictive distributive pattern except for the tremendously large values for both constituents at the St. Alban's Church well in the "badwater" zone. The mean calcium and magnesium concentrations are 78.5 mg/L and 30.62 mg/L respectively. Figure 21 presents a plot of calcium versus magnesium.

Sodium concentrations appear to plainly delineate the "bad-water" line. While the mean sodium value is 13.4 mg/L, all of the sampled wells that lie within 5000 feet (1524 meters) of the "bad-water" line (and Interstate 35) have sodium values greater than 25 mg/L including a concentration of 402 mg/L at the St. Alban's Church site. A sodium-chloride plot is illustrated in Figure 22. The mean potassium concentration is slightly larger than 2 mg/L in the study area.

No significant associations are evident between locations of lineaments and trace metal concentrations. Except for an anomalous value at Hays Hills Baptist Church (#58-58-1H), the mean concentration of aluminum is 0.06 mg/L. Both the aluminum concentration (0.16 mg/L) and the iron value (3.2 mg/L) are large at this well probably due

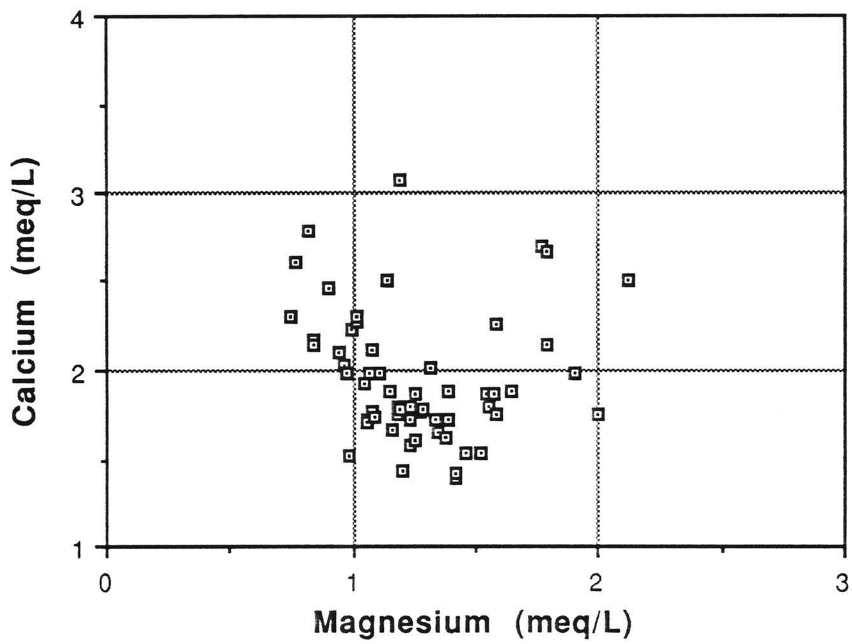


Figure 21: Calcium-magnesium relationship for samples collected in the study area

to its recent completion. Chromium, lead, and zinc concentrations are all relatively small with no anomalously large values measured among the 61 samples.

In this study, no correlation can be made between locations of lineaments and water chemistry. Perhaps a larger database could possibly reveal some type of relation. However, chemical analysis is a site-specific application. Not all linear features are necessarily predictive, thus, site-specific techniques such as water chemistry and dye tracing may not be the most appropriate tools for lineament analysis. In contrast, the combination of remote sensing of lineaments with their

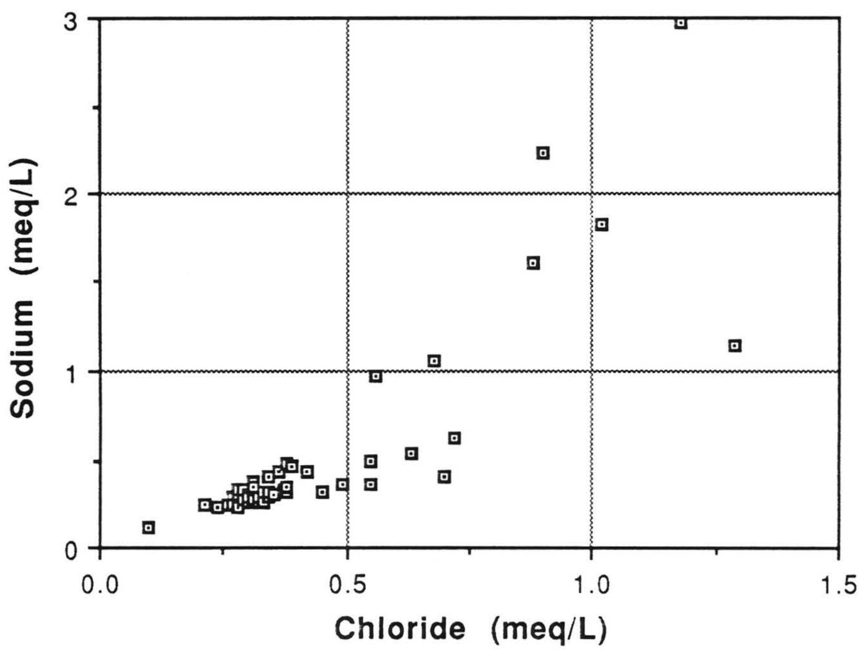


Figure 22: Sodium-chloride relationship for samples collected in the study area

statistical analyses can produce useful clues to the probable location of areas of increased permeability.

VI. Conclusions and Implications

This study investigates the correlations between structural lineaments and water-well yields in the Barton-Springs segment of the Edwards aquifer. In the Austin, Texas area, lineaments represent the structural grain of the Balcones-Ouachita fault zone and may indicate subsurface geologic phenomena such as faults, fractures, and joints. These structural features often represent discrete zones of large permeability, and thus, areas of enhanced flow of groundwater capable of conveying greater quantities of water than surrounding, non-fractured rock. Specific conclusions are:

1. Lineaments and fracture traces in the study area represent the tectonic stresses resulting from the Balcones-Ouachita structural belt and correlate with the primary fault trend of N 40 E and the corresponding joint trend of N 45 W.

2. The total length of lineaments in each 10° azimuth sector is a function of the number of lineaments within the sector rather than the length of the individual linear features.

3. Although any given lineament is not necessarily predictive of grain, the overall trend defined by all lineaments provides a clue to the structural grain in the study area. Likewise, the total number of lineaments is more important than the number of interpreters who identify a particular lineament.

4. A good correlation exists with increased specific-capacity values and decreased distances from each well to its nearest lineament, regardless of its classification. This correlation is especially evident for wells located within 200 feet of a lineament.

5. SW/NE trending lineaments have a greater influence on well yields than lineaments that are not oriented in this direction.

6. Wells located southeast of SW/NE trending lineaments indicate a greater correlation with specific-capacity values than do other wells.

7. Limited ranges for specific-capacity values of potential water wells in the study area can be reasonably estimated by measuring the distance from the well to the nearest SW/NE trending lineament located to the northwest of the well.

8. No direct correlation between locations of wells with respect to lineaments and water chemistry can be made for this particular study.

It is important to recognize that using the described lineament analysis to locate water wells will not necessarily guarantee success. Any particular well may fail to intersect a sufficient number of subsurface fractures to provide the well yield required to satisfy its desired use. Also, a particular fracture or set of fractures that may be intersected in a well may not have a sufficient storage and transmission capability to produce a large well yield. However, the use of the described lineament analysis to locate water wells can maximize the probability of obtaining a large-yield well.

Fracture-trace and lineament analysis can be particularly useful in determining the locations of groundwater monitoring wells. Because groundwater flow preferentially follows the most permeable pathway, monitoring wells should be based on fracture traces or lineaments. For example, if a hazardous-waste storage lagoon is located in an area of fractured bedrock, at least one of the downgradient monitoring wells, as required under the Resource Conservation and Recovery Act, should be located on a fracture trace or lineament.

Lineaments provide the hydrogeologist with a tool for predicting possible sites of environmental sensitivity particularly with respect to groundwater resources. Examples include the siting of groundwater monitoring wells for point sources of pollution, predicting the likely underground flow paths of a pollution plume or potential recharge enhancement dams. Thus, the location, orientation, and density of structural lineaments, along with the described statistical analyses of lineaments, will provide the water resource manager with the ability to identify discrete groundwater flow paths, predict contaminant-plume migration and, subsequently, to apply appropriate mitigation procedures.

Future research should focus on improving the understanding of the hydraulics of the Edwards aquifer. To this end, validated specific-capacity data should be acquired in the field from various well locations throughout the aquifer. Long-term pump tests should be conducted to complement specific-capacity data. Down-hole geophysical techniques could be employed to identify subsurface cavities. If the results conform to this study, a water well should be drilled to the southeast of a SW/NE trending lineament to substantiate the results presented in this paper. In addition, further study is needed to determine the change in groundwater flow paths with decreasing water levels in the Edwards aquifer.

VII. Appendices

A. Previous Pump Tests in the Edwards Aquifer

Due to the paucity of aquifer test data in the Barton-Springs section of the Edwards aquifer, the results of four pump tests, conducted by private hydrogeological consulting firms, are described below to illustrate the extreme ranges of transmissivity, permeability and specific-capacity values in the study area. The karstic features of the Edwards result in turbulent flow through crevices, dissolution cavities, fractures, and channels throughout conditions of varying hydraulic gradients, air entrapment, and hydrostatic pressures. This accounts for the widespread variation in evaluation of the aquifer at a specific location. Locations of the following wells can be found on the Plate 1.

<u>Well #58-42-821</u>

In January 1982, Underground Resource Management, Inc. of Austin, Texas was retained to review the records related to a water well located at 2502 Loop 360 South, Austin, Texas. The 460-foot (140 meter) deep well was drilled and completed in April 1981 by Central Texas

Drilling Company. As indicated in the driller's report, 6-5/8" diameter steel casing was set from ground surface to 350 feet (107 meter) below the ground surface. After completion, a 2 h.p. Red Jacket submersible pump was installed in the well.

On February 2, 1982, a pumping test was performed to determine the specific capacity of the water-supply well. The static water level was 262.2 feet (80 meter) below the top of the casing. The pumping rate was measured at 16 gpm with a maximum drawdown of 10.4 feet (3.2 meter) after 90 minutes of pumping. The resulting specific capacity of the well was calculated to be 1.54 gpm/ft of drawdown.

<u>Well #58-50-731</u>

In 1983, Underground Resource Management, Inc. of Austin, Texas supervised the installation of a water well for the Shady Hollow Estates Subdivision north of Manchaca, Texas. A 6.5 inch (16.5 cm) diameter test hole was drilled by Central Texas Drilling Company to a depth of 420 feet (128 meters). As noted in the driller's log, large fractures were first encountered at a depth of 231 feet (70 meters) (509' msl). From 231 feet to 330 feet (101 meters) (410' msl) the action of the drill stem and the nature of the returns from the hole suggested that solution enlargement of the secondary fractures associated with the fault had been extensive. The quantity of water blown to the surface with the returns increased substantially.

After the test hole was drilled to depth, it was reamed to a diameter of 9-7/8" to a depth of 438 feet (134 meters) (302' msl). At this depth, the density of encountered fractures had lessoned considerably and it was felt that the hole was nearing the bottom of the Edwards Formation. The hole was cased with 6-5/8" (16.8 cm) plain-end welded steel casing to a depth of 433 feet (132 meters) (307' msl).

In order to evaluate the potential of the well, a 24-hour pump test was conducted using a 10 h.p. Red Jacket submersible pump. The pump was set at 315 feet (96 meters) (425' msl) on 3" (7.6 cm) drop pipe with an airline strapped to the pipe. One inch (2.54 cm) diameter tubing was run alongside the drop pipe to a depth of 315 feet (96 meters) (425' msl). A pressure gauge attached to the airline and an electric probe run through the tubing were used to determine the change in water level throughout the test. At a pumping rate of 210 gpm, the water level inside the well was drawn down approximately 10 feet (3 meters) at the end of the 24-hour period. The resulting specific capacity of the well was calculated to be 21 gpm/ft of drawdown.

Well #58-58-2E

A pump test was conducted on Well #58-58-2E near Buda, Texas in November 1989 by Jack H. Holt & Associates, Inc. The property is located in Hays County approximately 2 miles (3.2 km) northeast of Buda at the southeast corner of Turnersville Road and the Interstate 35 frontage road. This site is owned by Hunter Industries and is used as a construction staging yard and a temporary concrete batch plant site.

A 700-foot deep (213 meters) well was drilled by Kucher Drilling of San Marcos, TX in October 1989. The 8 inch (20.3 cm) diameter well was cased to a depth of 460 feet (140 meters) and grouted with a cement slurry. A 20 h.p. submersible pump with a 3 inch (7.6 cm) discharge pipe was placed at a depth of 300 feet (91 meters) from the ground surface.

The purpose of the pump test was to determine flow rates, well drawdown, and possible effects of well drawdown on the Phillips Well located approximately 500 feet (152 meters) to the northwest. The pump discharge was a constant 200 gpm as verified by meter readings at the discharge pipe. The test was run for a period of 7 hours with a maximum drawdown of 117 feet (36 meters). The resulting specific capacity of the well was calculated to be 1.7 gpm/ft of drawdown. Water level in the well completely recovered within two hours. The discharge from the well did not effect the Phillips Well. Calculated transmissivity values were invalid due to erratic drawdown values caused by karstic groundwater flow.

<u>Well #58-57-8A</u>

In June 1990, Jack H. Holt & Associates, Inc. conducted a drawdown test at Native Texas Nursery in south Austin. The recently drilled well is located approximately 1.4 miles (2.2 km) south of Slaughter Lane and approximately 0.7 miles (1.1 km) east of Manchaca

Road. The water will be used for irrigation for a plant nursery of approximately 3.5 acres.

The Native Texas Nursery Well was drilled by Associated Drilling Company of Manchaca, Texas and completed on 26 June 1990 to a depth of 500 feet (152 meters). The well is cased with 5 inch (12.7 cm) diameter PVC to a depth of 500 feet (152 meters)and screened from 360 to 480 feet (110 to 146 meters). A 5 h.p. pump was set to a depth of 400 feet (122 meters) with a 1.25 inch (3.2 cm) PVC discharge. The discharge pipe is connected to a 2000 gallon steel storage tank approximately 15 feet (4.6 meters) from the well head.

A pumping test was conducted on 29 June 1990 to determine the productivity of the well. The static water level was 171.6 feet (52.3 meters) below the top of the casing. As verified by meter readings (in gallons), the pump discharge was a constant 36 gpm throughout the 6 hour test. With a maximum drawdown of 118.96 feet (36.3 meters), the specific capacity was calculated as 0.30 gpm/ft of drawdown. The aquifer transmissivity was determined to be 950.4 gal/day/ft.

B. Results of Chemical Analyses from LCRA Laboratory

Parameter	Units	Pool and Rogers Co. #58-58-219	Mystic Oaks WSC #1 #58-58-202	Cimarron Park #1 #58-58-114	Trigg Building #58-42-821	Suburban Austin WSC #58-50-733	Mr. Herb Mendieta #58-50-520	Park Hill Baptist Ch. #58-42-913	St. Alban's Epis. Ch. #58-50-854	Comal Tackle, Inc. #58-58-416
Alkalinity, total	mg/L	228	262	258	224	268	269	299	228	270
Alkalinity, bicarb.	mg/L	228	262	258	224	268	269	299	228	270
Alpha, gross	pCi/L	8.4	18.8	3.2	1.1	1.4	2.9	4.9		
Aluminum, dissolved	mg/L	0.04	0.02	0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
Arsenic, dissolved	mg/L	<0.01	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Barium, dissolved	mg/L	0.03	0.04	0.04	0.04	0.04	0.14	0.07	0.05	0.06
Boron, dissolved	mg/L	0.37	1.2	0.32	0.27	0.21	0.18	0.15	1.38	0.14
Cadmium, dissolved	mg/L	<0.01	0.03	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
Calcium, dissolved	mg/L	52.26	63.28	65.13	67.93	72.2	70.82	95.95	130.98	82.65
Carbon, total organic	mg/L	2	2	3	2	3	2	3	1.3	2
Chloride	mg/L	44	51	12	24	13	12	21	273	14
Chromium, dissolved	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper, dissolved	mg/L	<0.01	0.02	0.02	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
Flouride	mg/L	3.6	4	0.4	0.2	0.2	0.3	0.2	3.9	0.2
Iron, dissolved	mg/L	0.32	0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.08	<0.01
Lead, dissolved	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005	<0.005
Magnesium, dissolved	mg/L	35.58	46.26	27.58	21.81	23.4	25.65	20.09	99.84	21
Manganese, dissolved	mg/L	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mercury, dissolved	mg/L	<0.01	<0.01	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Nitrogen, Kjeldahl	mg/L	0.52	0.6	0.26	0.16	0.21	0.04	0.14	1.36	0.1
Nitrogen, ammonia	mg/L	0.62	0.67	0.06	0.09	0.2	0.24	0.07	1.19	0.06
Nitrogen, nitrate	mg/L	<0.01	0.02	1.94	0.58	1.42	1.48	1.53	<0.01	1.59
Nitrogen, nitrite	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Phosphorus, ortho	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01
Potassium, dissolved	mg/L	6.87	9.92	2.59	2.18	1.9	1.31	1.53	17.46	2.48
Total Dissolved Solid	mg/L	516	646	296	312	304	305	358	2012	348
Selenium, dissolved	mg/L	<0.005	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Silver, dissolved	mg/L	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Sodium, dissolved	mg/L	70.28	78.55	6.83	12.5	7.02	6.9	8.5	453.5	8.01
Strontium, dissolved	mg/L	27.16	30.29	0.74	0.43	1.18	2.71	0.19	21.54	0.27
Sulfate	mg/L	158	234	20	36	18	17	22	302	18
Total Hardness	mg/L	277	349	276	259	277	282	322	738	293
Zinc, dissolved	mg/L	<0.01	0.03	0.01	0.12	0.01	<0.01	<0.01	<0.01	<0.01
Silica	mg/L	11.46	12.73	10.2	8.89	10.14	10	10	14.36	11.19

B. Results of Chemical Analyses from LCRA Laboratory (cont.)

Parameter	Units	City of Buda Well #1 #58-58-403	Dahlstrom Middle Sch. #58-57-307	Village of San Leanna #58-50-855	City of Sunset Vall. #58-50-223	Chaparral Park #2 #58-49-911	Creedmoor-Maha #2 #58-50-847	Mr. J. D. Malone #58-50-852	Hays High School #58-57-901	Shady Hollow Est. #58-50-731	Goforth WSC #4 #58-58-508
Alkalinity, total	mg/L	276	262	224	288	292	240	222	250	277	228
Alkalinity, bicarb.	mg/L	276	262	224	288	292	240	222	250	277	228
Alpha, gross	pCi/L	4.5	2.3	7.1	1.2	7.3	7.3	6.9	2.9	1.8	5.1
Aluminum, dissolved	mg/L	0.02	0.01	<0.01	<0.01	<0.02	<0.02	<0.01	<0.01	<0.01	0.02
Arsenic, dissolved	mg/L	<0.005	<0.005	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Barium, dissolved	mg/L			0.07	0.32	0.12	0.12	0.05	0.03	0.03	0.07
Boron, dissolved	mg/L	1.1	0.47	0.14	0.08	0.11	0.06	0.14	<0.01	<0.01	0.02
Cadmium, dissolved	mg/L	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium, dissolved	mg/L	73.05	69.49	63.22	73.08	93.89	67.77	56.93	58.71	80.22	62.75
Carbon, total organic	mg/L	0.9	0.8	1.2	0.8	1.7	1.7	2	1.9	2	2
Chloride	mg/L	10	12	14	14	15	11	20	10	13	12
Chromium, dissolved	mg/L	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper, dissolved	mg/L	0.05	0.03	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
Flouride	mg/L	0.4	0.2	2.1	0.3	0.7	0.8	2.5	0.4	0.2	3.2
Iron, dissolved	mg/L	0.03	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.29
Lead, dissolved	mg/L	<0.005	<0.005	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Magnesium, dissolved	mg/L	26.34	24.68	30.58	31.75	51.38	26.12	33.11	28.32	23.67	35.75
Manganese, dissolved	mg/L	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mercury, dissolved	mg/L	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrogen, Kjeldahl	mg/L	0.16	0.07	0.03	0.03	0.12	0.33	0.29	0.16	0.11	0.06
Nitrogen, ammonia	mg/L	0.02	0.28	<0.01	<0.01	0.01	0.07	0.23	0.22	0.12	0.16
Nitrogen, nitrate	mg/L	1.9	2.08	0.04	2.91	0.46	1.21	0.23	0.74	0.93	<0.01
Nitrogen, nitrite	mg/L	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.02	<0.01	<0.01	<0.01
Phosphorus, ortho	mg/L	<0.01	<0.01	<0.01	0.15	<0.01	<0.01	0.02	<0.01	<0.01	<0.01
Potassium, dissolved	mg/L	<1.0	1.62	2.08	1.49	3.21	<1.0	2.56	1.93	1.47	1.38
Total Dissolved Solid	mg/L	325	302	414	328	556	340	390	276	312	444
Selenium, dissolved	mg/L	<0.005	<0.005	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005
Silver, dissolved	mg/L			<0.01	<0.01			<0.01	<0.01	<0.01	<0.01
Sodium, dissolved	mg/L	6.37	6.88	10.33	9.6	7.95	6.92	22.44	5.81	7.16	9.38
Strontium, dissolved	mg/L	11.07	0.25	41.78	0.98	8.48	23.38	28.28	2.42	0.47	46.11
Sulfate	mg/L	24	19	93	3	163	41	89	15	16	117
Total Hardness	mg/L	313	303	284	313	451	273	279	259	298	304
Zinc, dissolved	mg/L	0.01	0.11	<0.01	<0.01	0.02	<0.01	0.01	0.02	0.04	0.01
Silica	mg/L	10.7	10.16	11.62	14.39	12.94	10.78	11.66	10.91	9.54	12.42

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Lineament and Well Locations: Barton Springs section of the Edwards Aquifer, located in Central Texas.

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